CORRELATION BETWEEN IDAHO IT-144 AND AASHTO T-84 METHODS FOR IDAHO FINE AGGREGATES

A Thesis

Presented in Partial Fulfillment of the Requirements for the

Degree of Master of Science

with a

Major in Civil Engineering

in the

College of Graduate Studies

University of Idaho

by

Sandarva M. Sharma

Major Professor: Sunil Sharma, Ph.D., P.E.

Committee Members: Emad Kassem, Ph.D., P.E., Kenneth F. Sprenke, Ph.D., P.E.

Department Chair: Patricia J. S. Colberg, Ph.D., P.E.

August 2018

AUTHORIZATION TO SUBMIT THESIS

This thesis of Sandarva M. Sharma, submitted for the degree of Master of Science with a Major in Civil Engineering and titled "CORRELATION BETWEEN IDAHO IT-144 AND AASHTO T-84 METHODS FOR IDAHO FINE AGGREGATES," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor:

Sunil Sharma, Ph.D., P.E.	Date

Committee Members:

Emad Kassem, Ph.D., P.E.	Date
Kenneth F. Sprenke, Ph.D., P.E.	Date

Department Chair:

Patricia J. S. Colberg, Ph.D., P.E.	Date

ABSTRACT

The design of a Hot Mixed Asphalt (HMA) pavement mix requires information about the Bulk Specific Gravity (G_{sb}) and Absorption characteristics of the fine aggregates. This data is often determined using the standard AASHTO T-84 test for fine aggregates, which usually takes 2-3 days to complete. As the test is strongly dependent on the expertise of the operator, it has encountered ongoing criticism due to the subjective nature of the test. To overcome some of the operator-dependent errors associated with the AASHTO T-84 procedures, a new method, known as the CoreLok method was developed. This method is quick, reliable, portable, and provides consistent, repeatable results for fine aggregates. The Idaho Transportation Department (ITD) has its own standard procedure for the CoreLok test, IT-144 (2008), which is based on the original ASTM standard D7370. As the CoreLok test may be completed on an aggregate sample within 30 minutes, it has become a popular replacement for the AASHTO T-84 test.

This study was conducted to develop models which could correlate the IT-144 test results with AASHTO T-84 test results. For this purpose, 22 typical aggregate samples collected from the popular quarry sites in five ITD districts used by the ITD were tested using AASHTO T-84 and Idaho IT-144 test methods. A Round-Robin experiment was carried out involving ITD (Boise), ALLWEST and STRATA to confirm that the results were comparable between the participants. A total of 68 T-84 tests and 65 IT-144 tests were run at UI for the data analysis. Regression models were developed to predict the AASHTO T-84 values using the IT-144 values which were validated using the ALLWEST values.

Simple regression analysis and multiple regression analysis were performed to develop linear and non-linear prediction models. AASHTO T-84 results were used as the dependent variable and IT-144 test results, and other variables like particle sizes, Specific Surface Area (SSA) and Fineness Modulus (FM) of the aggregates, Coefficient of Curvature (C_c), and Coefficient of Uniformity (C_u) were used as the predictor variables. A simple linear regression model with R^2 = 90.53 percent and a multiple regression model with R^2 = 85.77 percent was recommended for $G_{sb,Dry}$ and Absorption prediction respectively. Data validation was better for simple linear regression for $G_{sb,Dry}$ and multiple regression for Absorption. It is recommended that the Idaho IT-144 test method be adopted as it is faster, easier, repeatable, and produces results which are close to the AASHTO T-84 method.

Keywords: Correlation, AASHTO T-84, IT-144, Specific Gravity, Absorption, Fine Aggregates

ACKNOWLEDGEMENTS

I would like to express my gratitude towards my academic advisor, Dr. Sunil Sharma for his immense support and encouragement throughout my studies and research. He has been a role model for me in my academic career and in my life.

I would also like to thank my committee members: Dr. Emad Kassem and Dr. Kenneth F. Sprenke for providing continuous support and guidance throughout this research. I would also like to thank Mr. Don Parks, CEE technician, for helping me in the laboratory.

Lastly, I would like to thank all of the graduate students in the Department of Civil and Environmental Engineering for their support throughout my research.

DEDICATION

To my family who has always been there for me!

To all of my friends at the University of Idaho and around the world for making my life joyful!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

1.1 Overview and Problem Statement

The design of a Hot Mixed Asphalt (HMA) pavement mix requires information about the Bulk Specific Gravity (G_{sb}) and Absorption characteristics of the fine aggregates. This data is often determined using the standard AASHTO T-84 test for fine aggregates, which usually takes 2-3 days to complete. As the test is strongly dependent on the expertise of the operator, it has encountered ongoing criticism due to the subjective nature of the test [1]. This concerns the reliable determination of a condition known as, "Saturated Surface Dry" (SSD), which contributes to variability, especially between different laboratories.

The use of erroneous G_{sb} values and absorption rates for aggregates used in HMA design results in mix volumetric errors, especially in the calculation of the voids in mineral aggregate (VMA) and asphalt content. This may result in bad design of the mix, and may cause early distresses on the pavement.

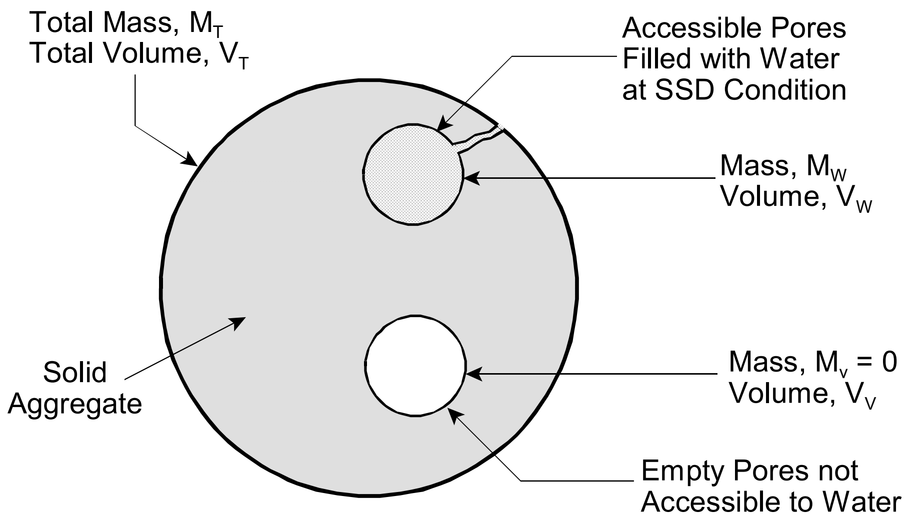
To overcome some of the operator-dependent errors associated with the AASHTO T-84 procedures, a new method which determines the volume of the aggregate using plastics bags and a vacuum chamber was developed about 20 years ago. This is known as the CoreLok method. This method is quick, reliable, portable, and provides consistent, repeatable results for fine aggregates. The standardized procedures for the test have been published as ASTM D7370. The Idaho Transportation Department (ITD) has its own standard procedure for the CoreLok test, IT-144 (2008), which is based on the original ASTM standard. As the CoreLok test may be completed on an aggregate sample within 30 minutes, it has become a popular replacement for the older AASHTO T-84 test.

Unfortunately, the results from the CoreLok tests are close, but not identical to the results produced by the AASHTO T-84 test. As ITD, and their consultants, prefer to use the much quicker CoreLok test, there is a need to investigate the reasons for the discrepancies between the two test procedures, and possibly, develop appropriate correlations for aggregates used in Idaho.

1.2 Objectives of the Study

For this study, typical aggregate samples will be collected from popular quarry sites used by ITD and the samples will be tested using the Idaho IT-144 and AASHTO T-84 procedures. After verifying the quality of the results, possible correlations will be proposed to estimate the AASHTO T-84 results using the readily obtained CoreLok values. Additionally, the study will examine the nuances of the AASHTO T-84 test procedures, and present recommendations that minimize operator dependent results.

1.2.1 Definitions of Specific Gravity



Volume of Solid, $V_S = V_T - V_V - V_W$

Mass of Solid, $M_S = M_T - M_W$

Figure 1.1 Definition of mass and volumes for an aggregate particle at SSD condition.

Specific gravity is defined as the ratio of mass of a volume of aggregate to the equivalent volume of water at a specific temperature. Figure 1.1 shows the masses and volumes for a unit aggregate particle that may be determined from IT-144 and AASHTO T-84 tests. By considering the volume of water permeable or impermeable voids in the aggregate, three different specific gravities are defined in practice [2].

1.2.1.1 Bulk Dry Specific Gravity ($G_{sb,Dry}$)

Bulk Dry Specific Gravity is defined as the ratio of the mass of solids (M_s) to total volume (V_s) of the aggregate particle. This value is smaller than the G_{sa} because it includes the volume of water permeable voids.

1.2.1.2 Bulk Saturated Surface Dry Specific Gravity ($G_{sb,SSD}$)

Bulk Saturated Surface Dry Specific Gravity is defined as the ratio of the total mass (M_T) of an aggregate particle to the total volume (V_T). The total mass of the aggregate includes mass of the solid and mass of water in the accessible pores at SSD condition.

1.2.1.3 Apparent Specific Gravity (G_{sa})

Apparent Specific Gravity is defined as the ratio of total mass (M_T) to volume of solids (V_S) of an aggregate particle. The volume that is considered here is the volume of the aggregates, excluding impermeable and water permeable voids. This value is the highest of all the specific gravities because it only considers the volume of solids.

1.2.1.4 Definition of Absorption

Absorption is defined as the percent increase of mass of the aggregates due to water in the water permeable voids at the SSD condition. This is the same as the gravimetric water content in percent.

If the masses and volumes are measured in grams and cubic centimeters, respectively, the following equations may be used to calculate the specific gravities.

Bulk Dry Specific Gravity, $$G_{sb,Dry} = \frac{M_T - M_W}{V_T} \tag{1.1}$$

Bulk SSD Specific Gravity, $$G_{sb,SSD} = \frac{M_T}{V_T} \tag{1.2}$$

Apparent Specific Gravity, $$G_{sa} = \frac{M_T}{V_s} \tag{1.3}$$

Absorption, $$Abs = \frac{M_W}{M_T - M_W} \times 100\% \tag{1.4}$$

Additional relationships between these four variables may be derived, as shown in the equations presented below.

Bulk SSD Specific Gravity, $$G_{sb,SSD} = \left(1 + \frac{Abs}{100\%}\right) \times G_{sb,Dry} \tag{1.5}$$

Apparent Specific Gravity, $$G_{sa} = \frac{G_{sb,Dry}}{\left(1 - \frac{Abs}{100\%} \times G_{sb,Dry}\right)} \tag{1.6}$$

Currently, there are two methods available for determining the Specific Gravity and Absorption properties of fine aggregates used for the design, and volumetric determination of Hot Mix Asphalt (HMA) for use in pavements. The two methods are: (1) Idaho test method IT-144, “Specific

Gravity and Absorption of Fine Aggregate using Automatic Vacuum Sealing (CoreLok) Method", and (2) AASHTO's standard method of test T-84, "Specific Gravity and Absorption of Fine Aggregate." Both methods require the accurate measurement of the volume of a piece of aggregate and the amount of water that may be absorbed by the dry aggregate.

1.3 Organization of the Report

This thesis consists of 7 chapters and an Appendix.

Chapter 2 presents a summary of the information gathered from a comprehensive literature review of research and findings concerning T-84 and CoreLok testing. At least five state DOTs have evaluated these tests and adopted guidelines for their use.

Chapter 3 concerns the samples of fine aggregates selected for testing, their descriptions, and sources. For this study, 22 samples from five out of six ITD Districts were tested for the development of useful correlations. The chapter also discusses the various procedures used to prepare samples for testing.

Chapter 4 discusses the testing procedures followed to determine the specific gravities and absorption properties. Specifically, there is a discussion of the Idaho IT-144 and AASHTO T-84 test methods. Additionally, with a view to minimizing variability, helpful information for completing these tests are presented along with appropriate recommendations.

Chapter 5 discusses the aggregate test results. The chapter discusses the Round Robin experiment, results from the five ITD districts, and presents a summary of the results used for the statistical data analysis.

Chapter 6 presents detailed information about the analytical methods used to develop practical correlations between the IT-144 and AASHTO T-84 results. Several regression models are presented in this chapter to estimate AASHTO T-84 values using the IT-144 values.

Chapter 7 provides a summary of the research performed, along with conclusions and recommendations for future research. The best regression model to correlate two test methods, IT-144 and AASHTO T-84, are presented with their R^2 values.

The complete calculations and results from testing 22 samples are presented in the Appendix.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter discusses the significance of the specific gravity and absorption parameters, as used for HMA mix design and volumetrics. This is followed by a discussion of the AASHTO T-84 and Idaho IT-144 test methods followed by a summary of the relevant literature reviewed for the project. Much of the literature on this topic concerned the assessment of the CoreLok method's ability to generate results that are comparable with the AASHTO T-84 method.

Bulk specific gravity (G_{sb}) is one of the most important parameters in the design of Hot Mix Asphalt (HMA) pavement mixtures, as the value is used in the calculation of Voids in Mineral Aggregate (VMA) [3]. Once VMA is calculated, its value is used in the calculation of effective binder volume.

Designing HMA mixture content also relies heavily on the water absorption capability of aggregates [4]. The aggregate absorption value depends on the aggregate type and typically varies from 0 to 5 percent. Miscalculation may affect the mix design, such that a lower calculation than the actual value may produce dry HMA leading to reduced durability of pavement. Conversely, higher values than the actual may require more asphalt in the HMA mixture producing pavement that is prone to rutting and other distresses.

There are traditional and new mechanical methods to measure the specific gravities and absorption of the aggregates. For this study, specific gravity and aggregate absorption are determined using two tests, IT-144 and AASHTO T-84.

Typical equations [5] used to calculate Air Voids (V_a), VMA, VFA and Volume of Effecive Binder (V_{be}) are:

$$V_a = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100 \qquad (2.1)$$

$$VMA = \left(100 - \frac{G_{mb} \times P_s}{G_{sb}}\right) \qquad (2.2)$$

$$VFA = \left(\frac{VMA - V_a}{VMA}\right) \qquad (2.3)$$

$$V_{be} = VMA - V_a \qquad (2.4$$

where,

G_{mb} = Bulk Specific Gravity of the compacted sample

G_{mm} = Maximum Specific Gravity of asphalt mixture

P_s = Percentage of aggregate in the total mixture

G_{sb} = Aggregate Bulk Specific Gravity

2.2 Standard Test Method (AASHTO T-84)

The Idaho Transportation Department (ITD) uses the American Association of State Highway and Transportation Officials (AASHTO) standard test method T-84 for fine aggregates. AASHTO T-84 is a standard method for determining Specific Gravity and Absorption of fine aggregates that pass the #4 sieve (4.75mm mesh). The critical part of the test is the determination of the Saturated Surface Dry (SSD) condition.

The cone test is used to determine if the aggregate has reached the SSD condition. This is basically a small-scale slump test indicating that the apparent cohesion between the aggregate particles is reduced allowing the cone to collapse. The cone test works well for aggregates which are natural sands, and rounded clean aggregates. With the growing trend of using manufactured aggregates, the cones may not slump readily and may cause problem with the determination of correct specific gravities and absorption values. For the aggregates that do not slump readily there are four criteria that can be used, as mentioned in Note 2 in AASHTO T-84 [2].

After the SSD condition is reached, the volume-displacement portion of the test starts by using the wetted aggregate in a pycnometer. This is followed by drying the aggregate and determining it's mass. The whole process takes approximately 24 hours to run [2]. The test method is discussed in greater detail in Chapter 3.

2.3 CoreLok Method (Idaho IT-144)

The CoreLok test method follows the ASTM D7370 standard and ITD has its own version called: Idaho IT-144. The IT-144 procedures are more recent (2008) and use the CoreLok device from Instrotek. IT-144 is an Idaho standard method of test for Specific Gravity and Absorption of fine aggregates using the automatic vacuum sealing (CoreLok) method [6]. IT-144 method addresses the drawbacks of AASHTO T-84 method in regards that it is an objective and faster test method to determine specific gravities and absorption [2]. For a typical test, the aggregate sample is oven dried and then divided into two portions, two 500 g and one 1000 g samples which will be used in two different parts of testing. In the first part of the test, the 1000 g aggregate is sealed in a bag in a vacuum chamber and opened under water to rapidly saturate the sample. The dry and submerged weight of the aggregate is used to calculate G_{sa}. The second part of the test uses a metal pycnometer (volumeter) and the remaining two 500 g sample. Bulk Dry Specific Gravity ($G_{sb, Dry}$) is calculated using the weight of volumeter filled with water, dry aggregate (500 g), and average weight of volumeter with aggregate and water only. These results are used to calculate the $G_{sb,SSD}$ and Absorption [6].

There are some aspects that could introduce errors in the test procedure. In the volumeter test, it is assumed that the oven dried aggregates absorb negligible amount of water during the two minutes of testing. Whereas, the amount of water absorbed depends upon two properties of aggregates, rate of absorption and absorptive capacity. Therefore, it is practical to assume that there is significant amount of water ingress into the water permeable voids of the aggregates during the two minutes of testing. Also, the test result for the vacuum chamber test could be affected by the duration and magnitude of vacuum applied to the plastic bag, and gradation of the aggregates [2]. More discussion about the test is given in Chapter 3.

Attempts have been made to minimize possible errors. The objectives of the study by Richardson and Lusher (2006) for Missouri DOT was to create a better calibration model for the CoreLok device to more reliably predict T-84/85 specific gravity values based on the CoreLok results [2]. It was believed that the increased confidence in using CoreLok method would be useful in quality control and quality assurance to determine the specific gravities and absorption of the aggregates.

The researchers accomplished this through multiple regression analysis on information from previously tested samples supplied by MoDOT that had been tested with both methods. In total, results from 233 unique samples were analyzed. The data were modified to remove certain non-natural sands (manufactured sands) which brought the total to 200 individual tests. Twenty random selections were removed from that dataset to use for independent model validation and the remaining 180 samples were used to create the correlation.

In the AggSpec software developed by Instrotek in 2002, corrections were made considering the variation in G_{sa} and G_{sb} values calculated using the two different test methods. Corrections were applied to the G_{sb} value obtained using CoreLok based on the laboratory work in which the actual water absorbed by the fine aggregates during the two minutes was taken into account. Later, Instrotek also corrected the Excel spreadsheet prepared by MoDOT. Corrections were made on both G_{sa} and G_{sb} values obtained from CoreLok test for fine and coarse aggregates. The correction was a simple linear correlation for the CoreLok-G_{sa} values to predict the T-84 G_{sa}. Correction of CoreLok-G_{sb} still posed a problem until three simple predictive models were developed by using T-84-Abs as a dependent variable and CoreLok-Abs as a predictor variable. One to relate G_{sb} from CoreLok to T-84/85 methods, one to relate G_{sa} from CoreLok to T-84/85 methods, and one to better calculate an intermediate value called CoreLok-Abs that helps arrive at the correlated value.

$$\text{CoreLok-Abs} = \frac{1-\left(\frac{\text{CoreLok-}G_{sb}}{\text{CoreLok-}G_{sa}}\right)}{\text{CoreLok-}G_{sb}} \times 100\% \tag{2.5}$$

SSD weight of the sample is calculated once the predicted CoreLok-Abs is obtained. The SSD weight of the sample when combined with submerged weight of the aggregates (obtained after corrections made in the CoreLok-G_{sa}), a corrected CoreLok-G_{sb} is obtained [2].

The researchers did a secondary analysis to discover other factors that might be used as predictor variables in a calibration model. They considered Los Angeles Abrasion and Micro-Deval tests because these are a good quantitative indication of aggregate mineralogy [2].

LA Abrasion and Micro-Deval were also shown to be statistically significant as predictor variables, though only in a preliminary sense. The correlation between G_{sa}/CoreLok-G_{sa} was found to be stronger than the G_{sb}/CoreLok-G_{sb}. The correlation between Abs/CoreLok-Abs was significant but was lower than the correlations between G_{sa}/CoreLok-G_{sa} and G_{sb}/CoreLok-Gsb. The researchers recommended using caution when applying the models to aggregate with a high specific gravity ($G_{sa} > 2.900$). They recommended follow-up work to correlate other tests that could characterize mineralogy, pore structure, or general geology such as LA Abrasion, Micro-Deval, Sulfate Soundness, Water-Alcohol Freeze, etc. In addition, they recommended that more data for aggregates with G_{sa} from 2.8 to 3.8 was required to develop a better predictive model which covers the full range of expected materials [2].

The purpose of the Florida study [1] was to evaluate the suitability of the CoreLok device to replace or supplement existing Florida DOT procedures. The researchers evaluated this objective based on the G_{mm}, G_{sb}, and G_{mb} for asphalt mixes, coarse aggregate, and fine aggregate. Seven fine aggregates were tested and a total of 28 tests were performed (7 aggregate types × 2 methods × 2 samples). The researchers found that the CoreLok device produces G_{sb} results equivalent to Florida DOT procedures for low absorptive aggregates (similar to the granites in this study). However, they recommended not to use the CoreLok for determining G_{sb}, G_{sa}, or percent absorption because it generally does not produce results consistent with Florida DOT procedures [1].

The purpose of the Australian study [7] was to determine whether the CoreLok is practical, reliable, and accurate. This study used only asphalt pucks (gyratory compacted samples) or roadway cores. Cores were cut on top and bottom to produce right cylinders. Thirty-nine samples of three different mix designs were tested using three different methods: SSD (essentially the AASHTO T-166, T-275, or T-331 method), mensuration (i.e. physically measuring the samples with calipers to determine volume), and CoreLok for a total of 117 tests (39 samples × 3 methods). The researchers only measured the G_{sb}. Twenty dense-graded asphalt samples were used to test for damage from repeated vacuum cycles. Of these, 10 served as a control (no cycles in the CoreLok) and the other 10 were cycled three times through the vacuum and venting process. Finally, three samples from each mix design were tested for repeatability i.e., whether one machine produces the same result multiple times in a row from the same sample) using each of the three methods for a total of 81 tests (3 methods × 3 replicates × 9 samples).

The researchers found that the CoreLok estimated the air voids to be about three percent higher than the SSD method for samples with air voids less than eight percent and the SSD method was likely to give erroneous results for samples with air voids greater than eight percent. In addition, they found that the CoreLok delivered the most repeatable results, and the physical measurement approach generated the least repeatable values for asphalt having 4 to 27 percent air voids. No noticeable change in physical properties occurred after repeated tests in the vacuum chamber.

The objective of the Ohio DOT study [8] was to develop an experiment and prepare samples to compare Ohio DOT's current procedures (based on AASHTO standards) to the CoreLok device. The study team comprised of University of Cincinnati researchers, Office of Material Management, ODOT, and Valley Asphalt Corporation. The goal was to determine whether the CoreLok had potential applicability to Ohio's conditions. For this, three experimental variables were selected: type of asphalt mix, aggregate source, and compaction levels. The researchers tested six different asphalt mix designs containing limestone, gravel, and limited amounts of slag. Gyratory compacted samples were made from each mix design and tested with the AASHTO standard and the CoreLok. A pilot study was carried out for selected samples to establish a common ground for the test procedures. A total of 109 G_{sb} and 33 G_{mm} tests were performed on the samples.

A statistical paired t-test was run to compare the means of G_{mm} for the 33 samples for the two test methods. The result showed a p-value of 0.99 which showed that there was no statistically significant difference between the two test methods. To establish a statistical relationship between the test methods, a regression analysis was performed. The analysis used correlation coefficient (R) rather than the coefficient of regression (R^2) value because the R^2 values gives the total variation in the values between the two test methods. The correlation coefficient represents how best the two test procedures are related to each other based on the linear relationship established between them.

Similar analysis was performed for the G_{sb} using results from 109 samples for the two test procedures, AASHTO and CoreLok. A p-value of 0.00 at 95 percent confidence interval was obtained which rejected the null hypothesis: the difference between the average CoreLok and average AASHTO G_{mb} value = 0. This showed that there was a statistically significant difference between the two test procedures. To understand the probable effect of the experimental variables on the result obtained, the data were divided into sub-groups based on four mix types, three aggregate types and two compaction levels. A paired t-test was performed to see if the results from the two test procedures are statistically different. The p-value for all the tests was obtained as 0.00 at 95 percent confidence interval, showing that the difference between the two test procedures was statistically significant. The analysis showed that the difference was significantly different between the test procedures regardless of the variables type of asphalt mix, aggregate source, and compaction levels.

The researchers noted that Ohio asphalt mixes are always designed to have two to six percent air voids and aggregate absorption is typically less than two percent. They also noted that true specific gravity values are somewhere between the CoreLok and AASHTO values, but that AASHTO is always used as the benchmark. At the end, they concluded that the CoreLok device produces precise, consistent, and repeatable test results within a shorter testing time, and recommended that Ohio DOT develop a correlation factor to relate the CoreLok results to the equivalent AASHTO results.

The objective of the Oklahoma DOT study [9] was to determine if the AggPlus/CoreLok or SSDetect system would produce statistically similar results to standard AASHTO T-84/85 procedures and evaluate each method's ease of use. SSDetect measures the SSD condition of the fine aggregate using an infrared light source tuned to water. To accurately measure the SSD condition, the amount of infrared reflectance is measured. The researchers tested 15 different samples of fine aggregate (in addition to coarse aggregate and blended samples) comprised of limestone, sandstone, granite and rhyolite, and natural sands and gravels. They performed a total of 180 tests (3 methods × 2 operators × 2 replicates × 15 sources).

After performing the tests, the researchers concluded that the CoreLok G_{sb} and G_{sa} were statistically similar to AASHTO T-84/85 but the CoreLok percent-absorption was statistically different from AASHTO. They also determined that the CoreLok produced a lower average standard deviation for G_{sb}, G_{sa}, and percent-absorption than the other methods. They also concluded that the procedure was easy to perform, and took the least time. The researchers recommended a round-robin testing program within the state to verify the results for fine aggregates.

Prowell and Baker [3] evaluated the SSDetect and CoreLok methods for determining the dry bulk specific gravity (G_{sb}) of fine aggregates. Each method was evaluated against the standard method described in AASHTO T-84. The evaluation was based on a round robin study with twelve labs and six materials, four crushed and two uncrushed (natural) fine aggregate sources. The new test procedures, SSDetect and CoreLok were checked for bias and precision.

Here, bias is defined as the difference between the measured value and the true value of the measured property. Precision is defined as the measure of variability of the test procedure and the repeatability by a single operator or between two different laboratories.

Until this day, there is no fine aggregate sample whose actual specific gravity is precisely known. Comparisons were made between the values obtained from two test methods with the AASHTO T-84, because it is the accepted method at present. Analysis of Variance (ANOVA) was used to observe the interaction between the response and factors using the statistical software, Minitab. G_{sb}, G_{sa}, and Absorption were used as the response variables separately with material types and method of testing used as the factors.

Material types, test method, and the interaction between them were all found to be significant for G_{sb}, G_{sa}, and Absorption. For each material, separate one-way ANOVA were carried out. Tukey's family error rate comparison was used to compare the confidence interval at five percent significance level for the mean G_{sb}, G_{sa}, and Absorption for each test method. The statistical difference between the test methods AASHTO T-84 and CoreLok for G_{sb}, G_{sa}, and Absorption are given in Table 2.1.

Table 2.1 Precision estimates

Method	Within Laboratory (Single Operator)		Between Laboratory (Multi-laboratory)	
	CoreLok	T-84	CoreLok	T-84
Pooled Standard Deviation (1s)				
G_{sb}	0.0440	0.0157	0.0519	0.0230
G_{sa}	0.0230	0.0093	0.0238	0.0151
Absorption (%)	0.3618	0.2170	0.5709	0.4380
Acceptable Difference Between Two Results (D2S)				
G_{sb}	0.1245	0.0443	0.1468	0.0651
G_{sa}	0.0651	0.0264	0.0672	0.0428
Absorption (%)	1.0233	0.6137	1.6148	1.2389

ASTM 691 software was used to calculate the precision of test methods from the round robin results. The precision has two components: repeatability and reproducibility. Repeatability is the standard deviation of the test results within a laboratory whereas reproducibility is the standard deviation of the test results between two laboratories.

Prowell and Baker found that statistical differences exist between the automated methods (Corelok and SSDetect) and AASHTO T-84 [3]. The SSDetect method showed lower variability compared to AASHTO T-84, as shown in Table 2.1. Prowell and Baker concluded that the precision of the CoreLok method was not as good as AASHTO T-84 and that the precision of the CoreLok method could improve with the familiarity of technicians with the procedure [3].

The purpose of the West Virginia study [10] was to evaluate different methods for measuring aggregate specific gravity for slag and limestone, and statistically compare the results with AASHTO methods. The researchers used 9 alternative methods to the standard AASHTO procedures ranging from modified AASHTO procedures to the CoreLok method. The study did not make any attempt to verify if another state's methods could find results similar to those of the standard AASHTO methods. Only two aggregate sources were tested – limestone and slag. A total of 30 samples were prepared and tested using 10 methods. Each sample being tested three times. The researchers found that there were statistically significant differences between the CoreLok method and the established AASHTO T-84 method results. They recommended that further research be done on other aggregate types and the department should continue to use the AASHTO T-84 test method.

The standard methods of testing AASHTO T-84 and T-85 are not typically used in practice for quality control because of the time it takes to run those tests. Vacuum-sealing method or CoreLok method removes the sample soaking time and the time to reach the SSD state in T-84. Hall [11] in his study measured the specific gravity and absorption of the aggregates using both traditional and vacuum methods. Six coarse and four fine aggregate were selected with different types of mineralogy. Tests were performed on five replicates of each aggregate sample.

Hall [11] states that values of G_{sa}, G_{sb}, and Absorption are used in the calculation of volumetric properties of hot-mix asphalt and are also important in obtaining the field density and proper compaction. It is of high priority to the material engineer to accurately and consistently measure the specific gravity and absorption while designing any civil engineering structures. The objective of the study was to evaluate the CoreLok method for its suitability in determining the specific gravities and absorption of different types of aggregates.

For the study aggregates of different types like limestone, sandstone, granite, gravel, and natural sand were selected. All the aggregates were crushed and sampled from in-service stockpiles at the material production facilities. The AASHTO T-84/85 and CoreLok test methods were used and a single operator performed all the tests to minimize variability. To attain a more realistic measure of variability, a random testing sequence was adopted [11].

When all the values for aggregates were obtained for different tests, the values were averaged. The mean values for the fine aggregates are tabulated in Table 2.2. Two statistical tests, the F-test and t-test, were used to see whether the test methods are statistically significant with respect to the results. A significance level of five percent ($\alpha = 0.05$) was used for the analyses.

Table 2.2 Mean specific gravity and absorption results for individual aggregates

Aggregate	Mean Absorption (%) (5 replicates)		Mean Specific Gravity[1] (5 replicates)			
			Apparent, G_{sa}		Bulk, G_{sb}	
	AASHTO	CoreLok	AASHTO	CoreLok	AASHTO	CoreLok
GRSC	1.30	0.66	2.650	2.646	2.601	2.562
SSSC	2.37	2.10	2.669	2.658	2.510	2.518
DFLL	0.14	3.28	2.638	2.622	2.629	2.415
SAND	0.41	0.51	2.651	2.639	2.623	2.604

Almost half of the results for G_{sa}, G_{sb}, and Absorption were observed to be significantly different at the 95 percent confidence level. The results showed that for Absorption values of less than one percent, CoreLok overestimated the absorption values and for 1.0 to 2.5 percent, CoreLok underestimated the absorption capacity. CoreLok underestimated the G_{sa} for fine aggregates, and the mineralogy did not play any significant role. A determining factor could not be identified for the G_{sb} as the results were not consistent with mineralogy or the higher or lower absorption values. The findings and the analyses of variability of the test results agreed with those reported by Prowell and Baker [3].

Hall [11] in his study concludes that the CoreLok method could be a likely alternative to the traditional method to measure the specific gravities and absorption of the aggregates. Also, based on the test results carried out by Hall [11], before the CoreLok method can be considered as a replacement for the AASHTO procedure, the CoreLok results have to be consistent and comparable to the AASHTO methods.

It is really important to accurately determine the bulk specific gravity of the aggregate for the accurate calculation of the realistic volumetric properties of the compacted HMA mixtures. A team of Khandal, Mallick and Huner [12] performed a study to develop an equipment to determine the SSD condition of the fine aggregates with high precision and accuracy. The SSD condition is usually reproducible for the well graded natural fine aggregates whereas, for the crushed fine aggregates, the results are inconsistent.

[1] AASHTO T-84 and T-85 require expressing a specific gravity value to two decimal places; the values are shown with three decimal places for subsequent use in hot-mix asphalt applications.

Various studies have been done in the past to improve reproducibility of the bulk specific gravity results. Some of those are: a glass jar method [15], [16], Martin's wet and dry bulb temperature method [17], Saxer's absorption time curve procedure [18], and Hughes and Bahranian's saturated air drying method [19]. The proposed modifications to those methods either didn't provide a significant improvement in the result or were too elaborative to be used in the field or were not practical for an average laboratory.

To determine the SSD condition, Khandal and Lee [20], developed a colorimetric method which involved soaking of sample in water with a specific dye. The color of dye changed when dried and that stage was assumed to be SSD condition. This method had some drawbacks as the color was not distinct for dark aggregates, there was no mechanism to ensure that if some aggregates will dry up faster, and the color change relied on the subjective judgement of the operator, which could introduce errors in the process.

Dana and Peters [21], for Arizona Department of Transportation, tried a different approach to directly determine the SSD condition by using simple thermodynamic principles. Hot air was blown into a small rotating drum where the sample was placed. The temperature of the incoming and the outgoing hot air was monitored using thermocouples mounted at the inlet and outlet of the rotating drum. A steady value of the thermal gradient was observed when the aggregate was drying, but once the sample reached SSD condition, the thermal gradient suddenly dropped. The sample was then taken out of the drum for further testing. The first prototype of the equipment generated good results, but further development of the equipment did not materialize and it was also recommended to perform testing on a wide range of fine aggregates.

Krugler et al. [22] also proposed procedures for the determination of the SSD condition for the fine aggregates. They proposed four methods. The sample is assumed to be in SSD condition if it fulfils at least two of the procedures mentioned below.

1. An oven dried sample is used as a reference while drying the fine aggregate sample. When the drying sample has the same color as the oven dried sample (for comparison), then SSD condition is supposedly reached.
2. A sample is assumed to be in SSD condition if it no longer adheres to the bottom of the pan and flows freely when placed over a tilted pan.

3. A sample is assumed to be in SSD condition if it no longer adheres to the bottom of the trowel and flows freely as individual particles.
4. A sample is assumed to be in SSD condition if no more than one sample particle adheres to the packaging tape which is attached to the small block of tape (Supreme Super-standard gummed paper tape, 2-in. medium duty).

The equipment developed by Dana and Peters [21] at Arizona DOT was adopted for the study performed by Khandal, Mallick and Huner [12]. The average bulk specific gravity value for cone test and the drum test method were not significantly different for the natural sands. The absorption values for the crushed aggregates were lower for the cone method than the drum test method because the crushed aggregates are over dried before the cone slump. The resulting bulk specific gravity value is thus higher for the cone method than the drum method.

The second prototype of the drum equipment was developed to overcome the problems that were encountered in the first prototype and to improve the result. The equipment needed to shut automatically once the sample reached the SSD condition. This helps to ensure the repeatability and reproducibility of the test method. It was recommended to develop the third prototype as soon as possible. The recommendation was to develop the mechanism to record the mass fluctuation in the drum when the sample dries because that way the sample will not have to be removed from the drum for weighing after it reaches the SSD condition. This would help to ensure the repeatability and reproducibility of the test method.

After reviewing over 15 articles, the general consensus is that the CoreLok method is a viable alternative to the AASHTO T-84 test method to measure the specific gravities and absorption of the aggregates. Nevertheless, Hall [11] stated that to accept CoreLok method as a replacement for AASHTO T-84 method, the CoreLok results must be consistent and comparable to the AASHTO T-84 test method. Prowell and Baker [3] also concluded that the CoreLok was not as good as AASHTO T-84 based on the precision and they believed that the precision of the technician may improve with the familiarity. The study by West Virginia Division of Highway recommended further research on other aggregate types (other than those considered for the study) and for the meantime, the department should continue using the AASHTO T-84 method.

Some new methods, such as, SSDetect, CoreLok, and many other modifications in the standard test procedure have been proposed but more research is needed before these can be adopted over the current T-84 standard. More specifically, many of the correlations proposed in the literature are aggregate specific and should not be used for other materials without calibration.

CHAPTER 3 SAMPLES

3.1 Introduction

There are many aggregate sources available to ITD throughout Idaho. To focus on a limited number of samples, the Chief Materials Engineer in each ITD District (see Figure 3.1) was contacted and asked to provide details of their most popular fine aggregate sources. This survey was sent out in early February 2016, and finalized in late March 2016. From the results of the survey, representative aggregates were selected, and the ITD Districts were asked to send sack samples of 70-80 kg per aggregate source. A total of 22 aggregate samples were delivered by five ITD Districts to the University of Idaho lab in Moscow, ID, by the end of May 2016.

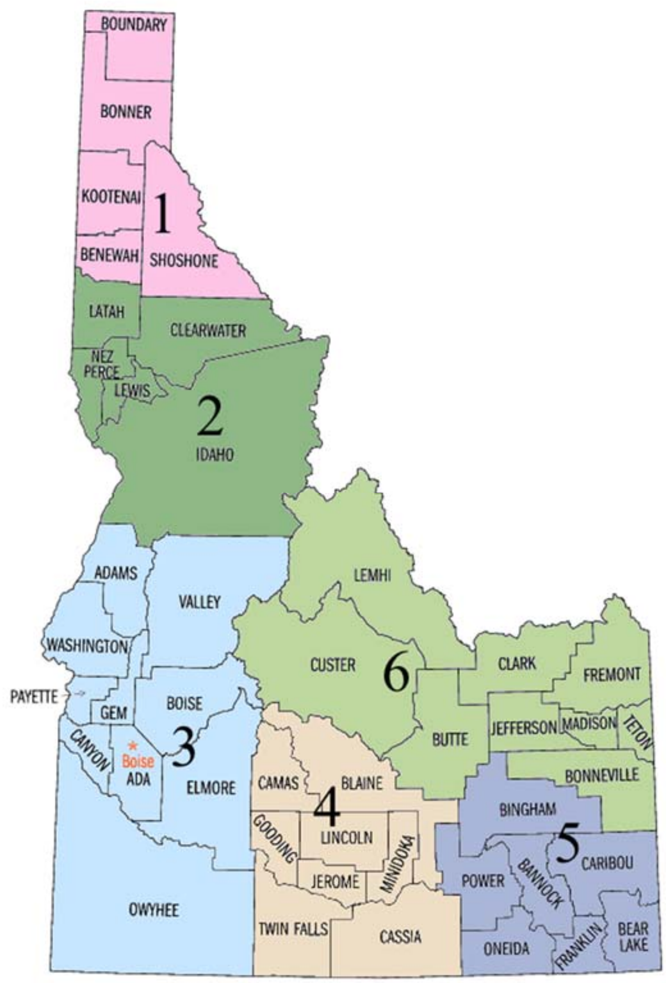


Figure 3.1 Idaho Transportation Department Districts

3.2 Material Selection

The sources of the 22 aggregate samples, and their mineralogy, are shown in Table 3.1. The Idaho Transportation Department aggregate identifier (ITD-ID), such as “Kt-213c”, is also included in the Table. Once the samples were received and logged, each sample was given a unique identifier. With this identifier, one can clearly recognize the district number and label assigned according to the testing sequence.

For example, the ITD-ID sample “Kt-213c” from ITD District 1 was labeled as “1D”. Here the first number represents the district, and the second alphabetic label “D” indicates that this is sample “D”, which implies that it was the fourth sample tested. With this labeling, one can quickly note that “A’ must have been the first sample tested, and the 22nd, and last, sample tested must be labeled “V”.

This identifier is further expanded for the testing phase, by adding numbers, and a unique identifier regarding the lab that performed the test. For example, a test labeled “UI-1D-02” indicates the second sample from aggregate “1D’, as tested by the University of Idaho, i.e. “UI”. The other identifiers for the labs involved in the project are: ITD – ITD lab, Boise, AW – ALLWEST, Meridian, and ST – STRATA, Boise.

3.3 Sample Preparation

For this study, plans called for testing each aggregate multiple times using the IT-144 and AASHTO T-84 procedures. For such a testing sequence, it is important that individual test samples be prepared carefully such that they are almost identical. For this project, a rigorous protocol was developed and followed closely to ensure that each prepared test sample was representative of the original aggregate. The sample preparation for each aggregate sample involved the following sequence:

1. Drying the entire sample;
2. Splitting the dried sample into roughly 15 kg portions;
3. Removing material greater than #4 (i.e. 4.75mm);
4. Washing the minus #4 material to remove fines, i.e. material passing the #200 sieve (0.075mm);
5. Drying the washed material;
6. Splitting all the dried, minus #4, washed material into approximately 4 kg samples. This size was selected as it allow splitting into sub-samples suitable for conducting one AASHTO T-84 test, and one IT-144 test from the 4 kg sample.

These preparation procedures are discussed in greater detail in the next section.

Table 3.1 Aggregate- ID, source location, and mineralogy

District	UI - ID	ITD - ID	Aggregate Source Location	Mineralogy
1	1P	Kt-215c	Hayden	Quartz
	1D	Kt-213c	Rathdrum	Quartzite, Argillite/Siltite, Calcareous Siltstone/Siltite, and Granodiorite
	1N	Kt-222c	Stateline	Quartz
2	2V	NP-82c	Atlas Concrete Pit	Basalt, Rhyolite, Quartzite, and Andesite
	2Q	Id-256c	Lamb Pit Camas Gravel	Basalt
	2T	WCW-18c	Poe Jorstad	Basalt
	2C	WCW-23c	Summit Stone Motley-Motley	Basalt
3	3H	Ad-161C	Knife River Amyx Pit	
	3J	Cn-140c	Idaho Materials and Construction Look Lane Pit	Granodiorite, Rhyolite/Dacite, Andesite, Basalt, and Quartzite
	3E	Ad-182c	C&A Paving	
	3A	Pit Ad136	Central Paving – Apple Pit	Andesite, Granodiorite, Rhyolite/Dacite, Basalt, and Quartzite
5	5R	Bk-100-c	JB Parson Co. Pocatello	Alluvial
	5U	Bl-93-s	Myron Earley, Ovid	Quartzite
	5S	Bg-107-c	Gale Lim Const., Blackfoot	Alluvial
	5O	Bg-111-c	Mickelsen Const., Blackfoot	Quartzite, Sandstone, Basalt, Rhyolite, Obsidian, and Opal
6	6K	Bn-156-c	HK Willow Creek Pit	Quartzite, Rhyolite, Basalt, Granodiorite, Sandstones, Chert
	6I	Bn-59-s	ITD Poplar Pit - Ririe	Quartzite, Limestone, Granodiorite, Diorite
	6M	Cl-56-s	ITD Ripper Pit - Dubois	Quartzite, Limestone, Basalt
	6G	Cu-75-s	ITD Pit – SH-75 Clayton	Quartzite, Rhyolite, granite, Argillite, Siltite, Siltstone, Dacite, Andesite, Gneiss
	6L	Le-160-c	Dahle Pit – US-93 Salmon River	Quartzite, Rhyolite, granite, Argillite, Siltite, Siltstone, Dacite, Andesite Gneiss
	6F	Le-96-s	Leadore Pit – Leadore	Quartzite, Limestone, Andesite, Schist, Gneiss
	6B	Fr-104-c	Teton Pit – Teton	Basalt, Rhyolite, Andesite, Obsidian, Granite, Quartzite, Chert

3.4 Reducing Samples of Aggregate to Testing Size

The delivered aggregate samples were oven dried first and split according to AASHTO T-248, to create uniform samples for testing. The splitter shown in Figure 3.2 was used to divide the dried aggregate to create consistent samples for testing. According to the standard, the splitter should have at least 12 equal width chutes for fine aggregates and the minimum width of the chutes should be at least 50 percent larger than the largest particle in the sample. A splitter with 16 equal width chutes was used, and had two catch pans to collect the split samples.

Figure 3.2 Splitter used to reduce samples to test size

3.5 Sieving to Remove Plus 4.75 mm Materials

Next, the split samples were sieved according to the standard AASHTO T-27. A large tray shaker, as shown in the Figure 3.3, was used to remove particle sizes greater than the #4 sieve (4.75mm).

3.6 Washing

The minus #4 samples were washed to remove fines (minus #200 material) following the AASHTO T-11 standard. The sample was agitated such that the fines were suspended in water and the runoff was drained through a No. 200 sieve. The No. 200 (75 µm) sieve was regularly inspected for cracks or holes. Nesting sieve, No. 16 (1.18 mm), with larger opening was used above the No. 200 (75 µm) sieve to protect the sieve underneath and also to prevent clogging. The sieve was washed using a rinsing bottle to remove the fines sticking to the No. 200 sieve.

Figure 3.3 Sieve shaker used for sieving

Figure 3.4 Washing of samples

3.7 Drying

The washed sample was oven dried at 230 ± 9°F (110 ± 5°C) following the AASHTO T-255 standard.

3.8 Preparing Samples for Testing

The dried, clean, minus #4 material was then reduced to testing size using the sample splitter. The aggregate sample was split into about four kg fractions and packed into plastic bags. The four kg amount is ideal for performing an AASHTO T-84 and IT-144 test. Some of the four kg samples were delivered to ITD-Boise, for testing by the ITD (Boise) lab, and by outside commercial labs, ALLWEST, Meridian, and STRATA, Boise.

3.9 Grain Size Distribution

There was some concern expressed that the multiple four kg bag samples prepared from one aggregate may have been split unevenly. Although there are no guarantees that the material in each bagged sample is identical, two bagged samples were selected from the 10 bagged samples prepared from aggregate 2E, and their grain size distribution checked for similarity.

The samples were sieved through sieve numbers 4, 10, 20, 40, 60, 100 and 200, and the grain size distribution of the two samples is shown in Figure 3.5. Results clearly showed that the two aggregate samples were uniform with a nearly identical grain size distribution. This confirmed that the splitting process worked well for aggregate 2E. If it worked well for this sample, it was assumed that the aggregate splitting process probably created uniform samples for all other aggregates as well.

3.10 Summary

The procedures discussed above were performed on all batches of aggregates to minimize sample variabilities and to ensure that the samples were similar to the best extent possible. The bagged, 4 kg samples were used for all AASHTO T-84 and IT-144 tests performed for this study by UI, ALLWEST, STRATA and the ITD (Boise) lab. The results of the aggregate testing are included in Chapter 5 and later analyzed in Chapter 6.

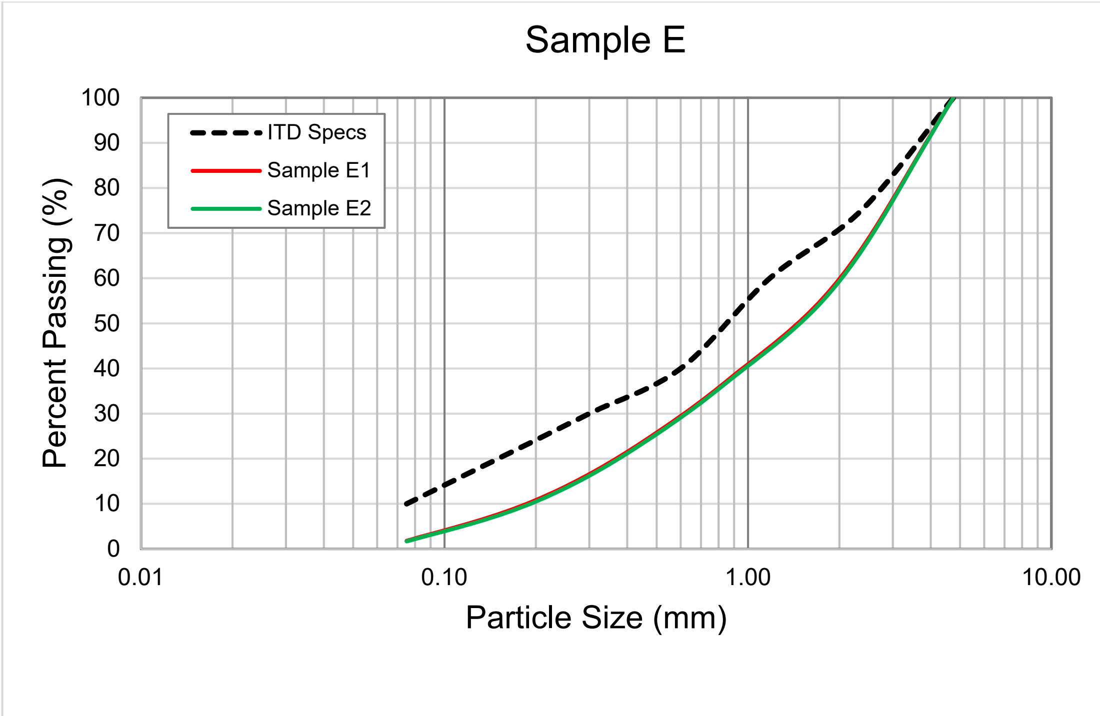


Figure 3.5 Grain Size Distribution (GSD) curve

CHAPTER 4 METHODOLOGY

4.1 Introduction

This chapter discusses the procedures followed for testing the fine aggregate. To determine the Specific Gravities (SGs) and Absorption, ITD relies on AASHTO T-84 and IT-144 standards. AASHTO T-84 is the standard test which is used nationally by most state DOTs with or without modifications. This test method has been in use for many years. However, as the AASHTO T-84 test method takes more time, the new automated CoreLok method has started to become more popular. The CoreLok test method follows the ASTM D7370 standard and ITD has its own version, Idaho IT-144, which was published in 2008. These two test methods are discussed in detail below.

4.2 IT-144 Method

The Idaho Transportation Department (ITD) follows the standard IT-144, "Specific Gravity and Absorption of Fine Aggregate using Automatic Vacuum Sealing (CoreLok) Method" for testing performed using the CoreLok device from Instrotek. This method is faster and has fewer apparent variabilities than the AASHTO T-84. For example, there is no need to soak samples and the only sample preparation necessary is oven drying the test sample. Other than the sample preparation, it takes only 30 minutes for testing. There are two parts to the test: (1) Using a metal pycnometer to determine weights, and (2) using the CoreLok vacuum chamber to effectively seal the dried sample using a vacuum, and then measuring the weight while the cut bag is submerged in water.

4.2.1 Procedures

The temperature of water used in this test procedure must be maintained at 25 ± 1°C (77 ± 2°F). Before starting the test, the pycnometer should be left in the water bath for conditioning such that it comes to the same equilibrium temperature. The pycnometer is then dried thoroughly using a towel.

4.2.1.1 Pycnometer Testing

This part of the test consists of a calibration followed by the actual test. For the calibration, the pycnometer is clamped over a plain surface and the level indicator is used to ensure that the clamped device is level. The pycnometer is filled with water to within 10 mm of the rim and isopropyl alcohol is sprayed on the surface if there are any air bubbles. The lid is placed on the pycnometer and locked. Using a syringe, water is injected into the pycnometer from the top center hole of the pycnometer until water comes out of a 3mm hole on the surface of the lid. This is an indication that the pycnometer is full. The application should be gentle and slow to ensure that no water bubbles are formed during the process. Water is wiped using a paper towel and the full pycnometer is weighed to the nearest 0.1 g.

This process is repeated three times. The readings should have a range within 0.5 g and averaged calibrated weight is used in calculations. This calibration procedure effectively determines the volume of the pycnometer.

The testing involves the use of a pycnometer which must be completed in less than two minutes. Water is added to halfway and 500 g of fine aggregate is slowly and evenly poured into the pycnometer. A metal spatula is used to stir the aggregate thoroughly, with the aggregate being gently pushed from the circumference towards the center of the pycnometer. The pycnometer is filled to within 10 mm of the rim with water and isopropyl alcohol is sprayed on the top to remove any air bubbles. The lid is gently placed on the pycnometer and locked. Using a syringe, water is slowly injected into the pycnometer. Any excess water is wiped from the pycnometer with a paper towel and the full pycnometer is weighed to the nearest 0.1 g.

The pycnometer is cleaned and the test is performed again with a fresh 500 g sample. The recorded mass in the two trials should be within one gram. If the difference is greater than one gram, a third test is performed and the masses are averaged for calculations.

4.2.1.2 CoreLok Testing

This part of the test involves the use of the CoreLok vacuum device. The CoreLok vacuum chamber is run in program 2 mode and the other settings are shown in Table 4.1. The immersed weighing basket is tared in the water bath where the temperature of water is maintained at a constant 25 ± 1°C. A small plastic bag, of size 10 × 14 inch, was used for all tests. All bags were carefully examined for holes, stress points, or folds before use.

The mass of the plastic bag is measured and recorded to the nearest 0.1 g. The one kg dried aggregate sample is poured into the plastic bag which is placed in the vacuum chamber and evenly spread. The bag should not be pressed from outside at any time. The open end of the plastic bag is placed over the seal bar and the chamber door is closed. The chamber door opens after drawing vacuum and the bag is sealed. It takes five to six minutes to create the vacuum and seal the plastic bag in the CoreLok machine.

The sample is gently removed and submerged in the water bath within five seconds of opening of the vacuum chamber. A small cut, approximately 50 mm (2 inches), is made on the top of the plastic bag. The bag is cut while submerged at least 50 mm below the water surface and at no time is the plastic bag brought outside the water bath. The immersed bag is held for 45 seconds to freely allow water into the plastic bag. During this process, the bag should not be shaken or squeezed because it may cause the loss of fines. Once the bag is filled with water, another cut, approximately 50 mm long, is made on the other side of the plastic bag. The top of the plastic bag is squeezed to remove the air bubbles by running fingers across the top.

The plastic bag is placed on the immersed weighing basket and water is allowed to enter. The weighing basket should not at any time touch the base of the walls of the water bath. The submerged mass is measured at the end of 15 minutes, recorded to 0.1 g. If the mass fluctuates by more than one gram at the end of 16 minutes, the mass is recorded at the end of 20 minutes. The data recorded are entered into the software, AggSpec, provided by the manufacturer. The software provides a report with Bulk Dry Specific Gravity, Bulk SSD Specific Gravity, Apparent Specific Gravity and Absorption values.

Table 4.1 Factory setting for CoreLok device

Control	Program #2	Description
Power Switch	On	Operation begins when lid is closed.
Vacuum Control	99%	Vacuum within chamber is 99% of absolute vacuum.
Dwell	300	Ensures that a vacuum of 99% is achieved.
Seal	1	Time setting of seal bar.

4.2.2 AggSpec Calculations

The AggSpec software, developed by Instrotek, uses the masses (in grams) collected during testing and performs the calculations shown below.

Pycnometer Test Data

Average calibration mass of pycnometer filled with water: $W_{calibration}$

Mass of dry aggregate for the pycnometer: W_{agg2}

Mass of pycnometer with aggregate W_{agg2} and water: W_{pycn}

CoreLok Test Data

Mass of plastic bag: W_{bag}

Mass of aggregate placed in the plastic bag: W_{agg1}

Mass of submerged aggregate in water: $W_{submerged}$

Calculations

1. Determine the Apparent Specific Gravity (SG) from the data collected from the CoreLok test. Volume of the plastic bag is obtained by dividing the weight of the bag by its density, 0.903 g/cm^3. Here, the volume of the aggregate sample is given by:

$$Volume = \left(W_{bag} + W_{agg1} - W_{submerged}\right) - \frac{W_{bag}}{0.903} \tag{4.1}$$

$$Apparent\ SG, G_{sa} = \frac{W_{agg1}}{Volume} \tag{4.2}$$

2. Determine the apparent SG from the pycnometer test. Here, the aggregate volume is given by

$$Volume = W_{calibraion} - \left(W_{pycn} - W_{agg2}\right) \tag{4.3}$$

$$App_{CL,SG} = \frac{W_{agg2}}{Volume} \tag{4.4}$$

3. Check to see if the pycnometer "$App_{CL,SG}$" value is greater than the CoreLok Apparent SG.

$$PA = \left(\frac{1}{App_{CL,SG}} - \frac{1}{G_{sa}}\right) \times 100 \tag{4.5}$$

If PA < -0.1, add 0.3 to PA, i.e. $PA = PA + 0.3$ (4.6)

This correction is proposed by the Instrotek.

4. Next, the absorption value is calculated using Instrotek's regression equation

$$PA_1 = 1.97675 \times PA + 0.28003 \tag{4.7}$$

5. After calculating the PA_1 value using Eq. 4.7, the following adjustments are made:

If $PA_1 < 0$, set $PA_1 = 0$

If PA_1 is less than 0.1, add 0.2 to PA_1, and

If PA_1 is less than 0.2, add 0.1 to PA_1

6. After these adjustments, the sample absorption will be equal to PA_1 in percent.

$$Absorption = PA_1 \tag{4.8}$$

7. Calculate the moist mass of aggregate using the above absorption value. Note that the "average" of the aggregate weight in the bag and pycnometer is used to calculate, X_1, the moist mass. The volume is calculated using the Apparent SG determined from the CoreLok data.

$$W_{avg} = \frac{1}{2}\left(W_{agg1} + W_{agg2}\right) \tag{4.9}$$

$$X_1 = \frac{Absorption}{100} \times W_{avg} + W_{avg} \tag{4.10}$$

$$Volume = \frac{Absorption}{100} \times W_{avg} + \frac{W_{avg}}{Apparent} \tag{4.11}$$

X_1 is the moist mass of the aggregate, and Volume is the volume of the aggregate with absorbed moisture.

8. Finally, Apparent SG (G_{sa}) will be calculated using Equation 4.2, absorption is given by the Equation 4.8, and bulk specific gravities are calculated by using Equations 4.12 and 4.13 which are as follows:

$$G_{sb,SSD} = \frac{X_1}{Volume} \tag{4.12}$$

$$G_{sb,Dry} = \frac{W_{avg}}{Volume} \tag{4.13}$$

4.3 AASHTO T-84 Method

AASHTO T-84 is the standard test method for the determination of specific gravity and absorption of aggregates. The test involves getting the aggregate to a condition known as SSD, and then using it find the apparent SG and Absorption.

Figure 4.1 Setup of the test and SSD condition

There are some concerns regarding this test procedure because of its sensitivity to techniques and operator experience, and the time it takes to perform a test. Moreover, there is always subjectivity regarding determination of the Saturated Surface Dry (SSD) condition using the cone and tamping technique. Because the slump not only depends on the moisture present on the outer surface of the aggregate, but also depends on parameters like particle shape and surface texture [1].

At first, a pycnometer is calibrated using water at 23ºC. The weight of the empty and water-filled pycnometer is measured in grams. This is the calibration part of the testing and determines the volume of the pycnometer.

For the test, approximately one kg of oven-dried, fine aggregate (passing 4.75mm sieve) is required for the test. The sample is allowed to cool, and then six percent moisture by weight of aggregate is added. The sample is mixed thoroughly and the pan is covered with aluminum foil and left to soak for the recommended 15 to 19 hours as shown in Figure 4.1.

After completion of the soaking period, the sample is spread on a dry non-absorbent mat and a gentle stream of cool air (using a fan) is used to dry the sample. The sample is stirred during the process for homogenous drying. The first cone test is performed after about five minutes of drying. At this stage, the first cone test is run to make sure that the sample has not dried beyond the SSD condition.

The drying process is continued by pouring the aggregate from one pan into the other, as shown in Figure 4.2. Figure 4.3 shows the process of tamping materials in the cone. This cone test will have to be repeated at frequent intervals as the sample gets drier.

Figure 4.2 Drying of sample using pans

Figure 4.3 Cone test

4.3.1 Cone Test for Determination of SSD Condition

The SSD condition is determined by filling a standard cone with moist aggregate, which is then lightly tamped. The SSD condition is presumed, if upon removal of the cone, parts of the compacted aggregate cone start to slump. Essentially, the procedure calls for checking for the SSD condition several times as the aggregate sample is dried from its original soaked condition. This procedure is described in greater detail below.

The empty cone is placed firmly on a clear plastic board and moist aggregate is added to the cone until it overflows the cone. Using a metal tamper with a mass of 340 ± 15 g, the aggregate is tamped 25 times. The tamper is allowed to fall freely through a height of 5 mm.

The over flow aggregates are cleaned from the base of the cone using a brush. Holding the top of the metal cone, the cone is lifted vertically and the state of the compacted cone is examined. There are three states possible, as shown in Figure 4.4.

1. If the compacted cone maintains its shape, the aggregate is still too wet. This is shown in Figure 4.4(a).
2. If a small portion at the top of the cone slumps leaving a flat aggregate surface equivalent to a dime on the top of the cone, this corresponds to the SSD condition. This is shown in Figure 4.4(b).
3. If a considerable portion of the compacted cone material falls apart, the sample is drier than the SSD condition. This is shown in Figure 4.4(c).

(a)

(b)

(c)

Figure 4.4 Various stages of the cone.
(a) Stage 1 – aggregate is too wet,
(b) Stage 2 – SSD condition,
(c) Stage 3 – Drier than SSD condition

So, with the above possibilities in mind, the test is repeated several times as the aggregate is dried from the soaked condition to the critical SSD condition.

Using the quartering method of splitting (Figure 4.5) to insure the homogeneity of samples, a representative 500 ± 10 g of the aggregate at the SSD condition is selected and added to the pycnometer filled partially with water. For testing performed at the University of Idaho, 500 ml flasks were used as pycnometers. Others have used 1,000 ml flasks for this part of the test.

Water is added to the pycnometer to fill it to 90 percent of its capacity as shown in Figure 4.6. The temperature of the water is checked to make sure that it is at the same temperature as used for the calibration.

Figure 4.5 Quartering of SSD aggregate sample

Figure 4.6 Pouring of SSD samples for de-airing

The pycnometer is agitated manually to eliminate the air bubbles and left still after agitation for about 20 minutes. The pycnometer is again agitated to see if there are more air bubbles. If foam (i.e. air bubbles) is present on the top of the water surface, a few drops of isopropyl alcohol are added. Finally, more water is added to bring the water level to the fill-mark in the pycnometer.

The pycnometer is left to sit in a water bath at controlled temperature for 16 hours to ensure that all air has been removed from the water. To complete the test, the aggregate in the pycnometer is poured into a drying pan and then dried in the oven for 24 hours. The final weight of the dried aggregates is used for the calculations.

4.3.2 Shortcomings of the AASHTO T-84 Test

The shortcomings of the AASHTO T-84 test are listed below [1].

- Determination of SSD condition of the fine aggregates may not be consistent using the cone and tamper method because the slump in the cone test is not only dependent on the moisture present on the sample but also on the angularity and the texture of the aggregate.
- The test requires an initial soaking period of 15-19 hours followed by overnight drying of the sample.

4.3.3 AASHTO T-84 Calculations

The measurements consist of the mass of the pycnometer with and without the SSD samples, and the mass of the aggregate at the SSD and dry conditions which is illustrated in Figure 4.7.

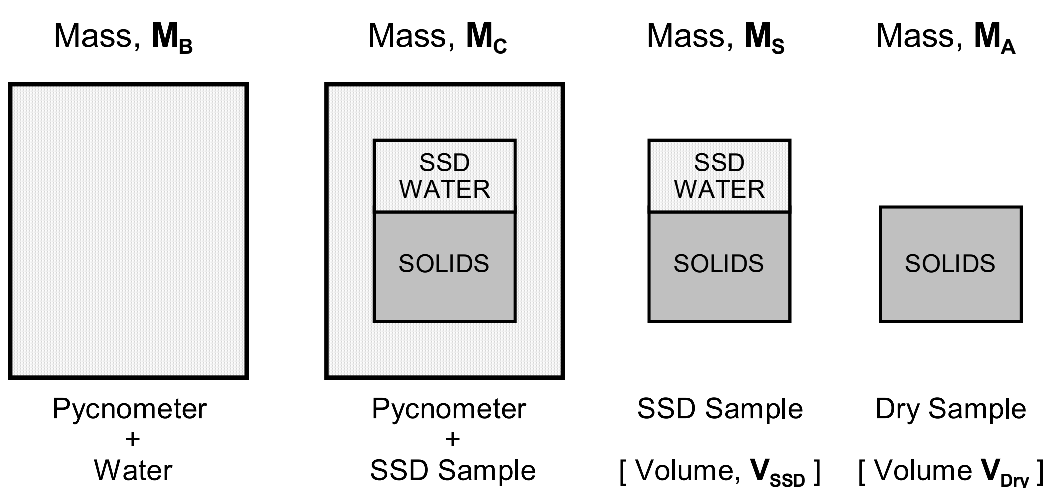


Figure 4.7 Data collected for T-84 testing consists of the mass (in grams) for the four conditions

For measurements made in grams, the volume of the SSD and dry samples may be calculated using the following expressions:

Volume of SSD sample: $V_{SSD} = M_B + M_S - M_C$ (4.14)

Volume of the dry sample: $V_{Dry} = M_B + M_A - M_C$ (4.15)

Once the volumes are determined, the required specific gravities and the absorption may be calculated using equations 4.16 – 4.19.

Bulk Specific Gravity, Dry: $$G_{sb,Dry} = \frac{M_A}{V_{SSD}} \quad (4.16)$$

Bulk Specific Gravity, SSD: $$G_{sb,SSD} = \frac{M_S}{V_{SSD}} \quad (4.17)$$

Apparent Specific Gravity: $$G_{sa} = \frac{M_A}{V_{Dry}} \quad (4.18)$$

Absorption (%): $$Abs = \frac{M_S - M_A}{M_A} \times 100\% \quad (4.19)$$

4.4 Variabilities in the Test Procedures

AASHTO T-84 is a more sensitive test to run than the IT-144. There are many variabilities that should be considered while performing the test. Also, AASHTO T-84 is a more operator dependent test which introduces more variabilities and potential errors. IT-144 has lesser variabilities than AASHTO T-84 because it does not rely on subjective judgement to identify the SSD condition of the aggregate.

The factors likely to affect AASHTO T-84 testing are noted as follows:

- Agitation and de-airing wait time (20 minutes or 16 hours)
- Sample weight equilibrium after drying in oven
- Tamper drop height
- Water temperature - maintained at constant 23 ± 1.7ºC
- Flask Size (500 mL or 1000 mL)

Tests were run to investigate the effects of these factors, which are discussed next.

4.4.1 Agitation and De-airing Wait Time (20 minutes or 16 hours)

The AASHTO T-84 standard recommends a vigorous agitation of aggregate in the pycnometer for 20 minutes, followed by drying to a constant mass. A test was performed to check on the deaerating process. The sample was agitated for the first 20 minutes and the weight was measured. The sample was then left in a water bath, maintained at 23ºC, for two hours and the sample was agitated vigorously before measuring the weight. This process was repeated after 16 hours. The changes in the weight of the pycnometer are shown in the Table 4.2.

Table 4.2 Change in weight after de-airing

	Weight (g)	
	Sample A	**Sample B**
Sample + Water to mark + Pycn (20 mins)	1015.4	1021.1
After water added to mark in 2 hours	1016.1	1022.2
Water added in 16 hours	0.7	1.1
Water added in 24 hours	0	0

In the test, 0.8 g of water was added at the end of 16 hours into the pycnometer. No additional water was required to fill the pycnometer at the 24-hour mark (i.e. after another 8 hours). As a result of this investigation, a de-airing time of 16 hours was followed for all the AASHTO T-84 testing.

Using the same data, no change was observed in the absorption value, but significant difference was observed in the calculated specific gravity values, as shown in Table 4.3.

Table 4.3 Test for agitation and de-airing time

De-airing Time	Specific Gravity			Absorption (%)	Remarks
	DRY	**SSD**	**Apparent**		
20 minutes	2.748	2.819	2.956	2.56%	none
2 hours	2.756	2.826	2.965	2.56%	0.5 g of water added
16 hours	2.762	2.833	2.972	2.56%	0.3 g of water added

4.4.2 Sample Weight Equilibrium after Drying in Oven

The aggregate from the pycnometer is oven-dried and then allowed to cool off before its weight is measured for absorption and specific gravity determination. The AASHTO T-84 standard recommends a cool off time of 1.0 ± 0.5 hours. To check the variation, a test was performed to see the effect of cooling time and the results are noted in Table 4.4.

Table 4.4 Variation of sample weight (in grams) with cooling

Time (min)	Weight of Pan 4 (Evaporating Dish)	Weight of Pan 7 (Evaporating Dish)
0	784.2	780.6
5	784.4	780.7
10	784.4	780.8
15	784.5	780.8
20	784.6	780.9
25	784.7	780.9
30	784.7	780.9

It was noted that the weight came to equilibrium after 30 minutes of cooling. Therefore, a cooling time of 30 minutes was adopted for all AASHTO T-84 testing.

4.4.3 Tamper Drop Height

The tamper fall height and speed of the tamping are important parameters in the cone test to determine the SSD condition. As per the AASHTO T-84 standard, the free falling height under the action of gravity must be 5 mm (0.2 in.) above the top surface of the fine aggregate in the cone [13]. Also, the number of blows should be 25. No additional fine aggregates should be added during the tamping process. Fall heights greater than 5 mm will increase the compaction energy imparted to the aggregate in the cone. With a higher compaction, the resulting cone may not slump even when the aggregate is at the SSD condition.

Tests were performed to check if the drop height was a consistent 5 mm. The test setup was as shown in Figure 4.8. To investigate this, a video of the tamping process was recorded and reviewed for inconsistencies. The slow motion video clearly depicted that the drop height was very close to 5 mm and the rate of tamping was consistent, with 25 blow being completed within 20 seconds.

Figure 4.8 Test for tamper drop height

4.4.4 Water Temperature - Maintained at Constant 23 ± 1.7ºC

The AASHTO T-84 standard states that the temperature of water should be maintained at 23 ± 1.7ºC during the testing. This temperature should be maintained during the calibration of pycnometer and also during the de-airing process. For all testing, a constant temperature of 23 ± 1.7ºC was maintained consistently throughout testing process.

4.4.5 Flask Size (500 mL or 1000 mL)

The AASHTO T-84 standard states that the size of the pycnometer should be at least 50 percent greater than the space required for 500 g of sample. Typically, a 500 ml pycnometer is used for the test. It is possible that a larger pycnometer may de-air the sample faster. To evaluate this possibility, a 1000 mL pycnometer was used for the test. The results showed that the size of the pycnometer did not have any effect on the de-airing time.

The IT-144 standards was strictly followed for the CoreLok testing whereas in AASHTO T-84, a modification was made in the de-airing time. The standard allows 20 minutes of vigorous shaking to de-air, whereas, a 16 hour wait time for de-airing was practiced to ensure adequate de-airing. The standard does not specify the wait time before taking the weight of hot samples from the oven. A wait time of 30 minutes was used in all the tests because the weight of the dry aggregate sample was stable after 30 minutes. The main focus in AASHTO T-84 testing was to minimize variabilities, and to perform the test according to a consistent procedure.

CHAPTER 5 AGGREGATE TEST RESULTS

5.1 Introduction

In this chapter, all results from testing the 22 aggregate samples according to the AASHTO T-84 and Idaho IT-144 are presented, along with an assessment of the quality of the test results. All of these test were completed according to the procedures discussed in Chapter 4. Recalling the concerns mentioned regarding the subjectivity of recognizing the "Saturated Surface Dry" (SSD) condition, the testing plan followed a special sequence of events to ensure a high level of quality assurance. The sequence required: (1) Initial testing at UI, (2) Training and evaluation at the ITD (Boise) lab, (3) A "round-robin" testing experiment involving ITD (Boise), and material testing consultants: ALLWEST (Meridian) and STRATA (Boise), and (4) final testing for 22 aggregates.

Initial familiarity with the equipment and testing procedures was achieved by performing tests on samples at the UI lab in Moscow, ID. These initial tests closely followed the published standards, AASHTO T-84 and Idaho IT-144. After erratic results at first, increased familiarity with the procedures and equipment led to more consistent results. At the end of this initial phase of preliminary testing, the only remaining concern was whether the cone and tamping process (AASHTO T-84) was being performed correctly, i.e. was the SSD condition achieved consistently. To eliminate these concerns, aggregate samples were transported to the ITD (Boise) lab for testing by the Boise and UI personnel.

5.2 Tests Performed in Boise

The Boise tests were conducted over a 2-day period, December 21-22, 2016. At this training session, Bob Englemann (lab manager) demonstrated the part of the AASHTO T-84 procedure concerning the drying process and attaining the SSD condition precisely. Following the demonstration, three other aggregates were tested by Sandarva Sharma (UI) and Travis Enzminger (ITD lab technician). The intent here was to perform the SSD portion of the test under supervision. While in Boise, six aggregates were also tested using the IT-144 procedure and the CoreLok device available in the Boise lab. The results of the tests performed in Boise by Sandarva Sharma (SMS) and Travis Enzminger (TE) are given in Tables 5.1 and 5.2.

A D2S range of 0.007 to 0.016, and 0.004 to 0.025 was observed between the tests performed at SMS and TE for $G_{sb,Dry}$ for the test methods AASHTO T-84 and IT-144 respectively. In reviewing and comparing the results from the AASHTO T-84 testing, it was agreed that the tests performed by Sandarva Sharma were comparable to the ITD results. The same conclusion was reached for the IT-144 tests performed using the metal pycnometer and the CoreLok vacuum chamber. Overall, this training session was a success as many important features, not mentioned in the standards, were adopted for future tests to be performed at the University of Idaho.

Table 5.1 AASHTO T-84 test results for the tests performed in ITD-Boise lab in December 2016

Sample ID	Test results in Boise (TE)				Test results in Boise (SMS)			
	Abs	G_{sa}	$G_{sb,SSD}$	$G_{sb,\ Dry}$	Abs	G_{sa}	$G_{sb,SSD}$	$G_{sb,\ Dry}$
Bg111c	0.60%	2.646	2.619	2.603	0.60%	2.657	2.633	2.618
Np82c	1.60%	2.799	2.722	2.679	1.50%	2.808	2.735	2.695
Cn140c	0.60%	2.639	2.612	2.596	0.80%	2.643	2.610	2.589

Table 5.2 IT-144 test results for the tests performed in ITD-Boise lab in December 2016

Sample ID	Test results in Boise (TE)				Test results in Boise (SMS)			
	Abs	G_{sa}	$G_{sb,SSD}$	$G_{sb,\ Dry}$	Abs	G_{sa}	$G_{sb,SSD}$	$G_{sb,\ Dry}$
Np82c (1)	1.60	2.822	2.745	2.703	1.40	2.806	2.736	2.697
Np82c (2)	1.70	2.802	2.772	2.677	1.60	2.813	2.736	2.693
Bg111c (1)	0.60	2.667	2.642	2.628	0.50	2.655	2.632	2.619
Bg111c (2)	0.60	2.668	2.642	2.627	0.50	2.652	2.632	2.620
Cn149c Virgin	1.70	2.681	2.610	2.567	1.80	2.662	2.587	2.542
Cn140c	1.10	2.649	2.601	2.571	1.00	2.646	2.602	2.575

5.3 Round Robin Testing

Once the initial training and testing was completed, it was agreed that four aggregate samples would be tested in the UI and ITD (Boise) labs for quality assurance in a "round-robin" experiment. The four samples selected were considered to be representative of the 22 aggregates collected from the ITD Districts. Parameters such as rock type, absorption, and particle shapes were considered in selecting these representative samples. The four samples selected for this experiment were:

1. Aggregate Sample 3A (Ad-136) from District 3;
2. Aggregate Sample 6B (Fr-104-c) from District 6;
3. Aggregate Sample 2C (WCW-23-c) from District 2;
4. Aggregate Sample 1D (Kt-213-c) from District 1;

These four samples were prepared according to the procedures discussed in Chapter 3 and shipped to the Boise lab. Each shipped aggregate sample package consisted of five 4 kg bags. The intent here was to use the material in one 4 kg bag to conduct one AASHTO T-84 and one Idaho IT-144 test. The UI lab completed tests on all four samples in March, 2017. However, due to time constraints, the ITD (Boise) lab was able to complete tests on only two samples, Samples 6B and 2C, by April, 2017.

As only two out of four samples had been tested, it was agreed in late May, 2017, that additional tests would be conducted by two local material testing labs, ALLWEST (Meridian) and STRATA (Boise). To get this underway, one more sample was added to the experiment as the ITD (Boise) lab had used up Samples 6B and 2C in completing their testing. The fifth sample selected for the round-robin experiment was Sample 3E from District 3. So, at the end Samples 3A, 6B, 2C, 1D, and 3E were added to the round-robin experiment by the end of July, 2017.

ALLWEST (Meridian) completed tests on Samples 3E, 1D, and 3A in early December, but STRATA (Boise) was able to only provide results for Sample 3E. STRATA (Boise) did test one or two additional samples, but due to personnel changes, the results of these tests could not be verified, and were thus excluded from the study. A summary of test results for all five aggregates is presented in Tables 5.3 to 5.7 for each selected sample.

Table 5.3 Round Robin Test results for Sample 3A

Sample Designation	**T-84**				**IT-144**			
	$G_{sb,Dry}$	**$G_{sb,SSD}$**	**G_{sa}**	**Abs (%)**	**$G_{sb,Dry}$**	**$G_{sb,SSD}$**	**G_{sa}**	**Abs (%)**
UI-3A-01	2.578	2.608	2.657	1.16%	2.589	2.616	2.662	1.07%
UI-3A-02	2.564	2.596	2.648	1.24%	2.586	2.616	2.665	1.14%
UI-3A-03	2.586	2.616	2.666	1.16%	2.589	2.616	2.661	1.05%
UI-3A-04	2.581	2.610	2.658	1.12%	2.587	2.615	2.662	1.09%
Average	**2.577**	**2.607**	**2.657**	**1.17%**	**2.588**	**2.616**	**2.663**	**1.08%**
Std. Dev.	**0.00817**	**0.00726**	**0.00638**	**0.04%**	**0.00130**	**0.00043**	**0.00150**	**0.03%**
COV	**0.32%**	**0.28%**	**0.24%**	**3.73%**	**0.05%**	**0.02%**	**0.06%**	**3.10%**
Range	**0.022**	**0.020**	**0.018**	**0.12%**	**0.003**	**0.001**	**0.004**	**0.09%**
AW-3A-01	2.591	2.615	2.653	0.90%	2.581	2.609	2.657	1.10%
UI-3A-05	2.597	2.623	2.666	1.00%	-	-	-	-

Table 5.3 above shows the test result of sample 3A. The Coefficient of Variation (COV) for G_{sb} and G_{sa} were all observed to be less than one percent, and the COV for absorption was observed to be around three percent. This showed that the variation in the test results was small and the tests were repeatable. A new set of tests were performed afterwards and the results were compared with that of ALLWEST. The values were almost identical and satisfied the D2S limit of 0.015 for $G_{sb,Dry}$. The low D2S value for ALLWEST and UI IT-144 test results showed that both the labs were performing the test in a similar manner.

Table 5.4 Round Robin test results for Sample 6B

Sample Designation	T-84				IT-144			
	$G_{sb,Dry}$	$G_{sb,SSD}$	G_{sa}	Abs (%)	$G_{sb,Dry}$	$G_{sb,SSD}$	G_{sa}	Abs (%)
UI-6B-01	2.381	2.473	2.599	3.40%	2.441	2.504	2.603	2.55%
UI-6B-02	2.391	2.472	2.601	3.38%	2.436	2.502	2.607	2.68%
UI-6B-03	2.393	2.473	2.599	3.31%	2.441	2.502	2.598	2.47%
UI-6B-04	2.387	2.468	2.597	3.39%	2.440	2.503	2.605	2.59%
Average	**2.388**	**2.471**	**2.599**	**3.37%**	**2.440**	**2.503**	**2.603**	**2.57%**
Std. Dev.	**0.00458**	**0.00206**	**0.00141**	**0.04%**	**0.00206**	**0.00083**	**0.00334**	**0.08%**
COV	**0.19%**	**0.08%**	**0.05%**	**1.05%**	**0.08%**	**0.03%**	**0.13%**	**2.94%**
Range	**0.012**	**0.005**	**0.004**	**0.09%**	**0.005**	**0.002**	**0.009**	**0.21%**
ITD-6B-01	2.429	2.503	2.623	3.03%	2.440	2.501	2.598	2.50%
ITD-6B-02	2.437	2.512	2.635	3.08%	2.457	2.509	2.593	2.10%
ITD-6B-03	2.424	2.497	2.613	2.98%	2.446	2.502	2.592	2.30%
ITD-6B-04	2.422	2.494	2.610	3.00%	2.462	2.514	2.598	2.10%
Average	**2.428**	**2.502**	**2.620**	**3.02%**	**2.451**	**2.507**	**2.595**	**2.25%**
Std. Dev.	**0.00579**	**0.00687**	**0.00978**	**0.04%**	**0.00870**	**0.00532**	**0.00277**	**0.17%**
COV	**0.24%**	**0.27%**	**0.37%**	**1.25%**	**0.35%**	**0.21%**	**0.11%**	**7.37%**
Range	**0.015**	**0.018**	**0.025**	**0.10%**	**0.022**	**0.013**	**0.006**	**0.40%**

Table 5.4 shows the test results for sample 6B performed at the UI and ITD-Boise lab. The COV for G_{sb} and G_{sa} for UI were all observed to be less than one percent and that for absorption was observed to be one and three percent for AASHTO T-84 and IT-144 test methods, respectively. Similar was the case with ITD-Boise lab, except COV was around seven percent for IT-144 which

could still be considered a good result. The D2S limit for UI results for T-84 and IT-144 satisfied the 0.015 limit for $G_{sb,Dry}$ whereas, that for ITD-Boise results for IT-144 was slightly higher than the 0.015 limit. The results also showed that the two labs were very good in producing similar results.

Table 5.5 Round Robin test results for Sample 2C

Sample Designation	T-84				IT-144			
	$G_{sb,Dry}$	$G_{sb,SSD}$	G_{sa}	Abs(%)	$G_{sb,Dry}$	$G_{sb,SSD}$	G_{sa}	Abs (%)
UI-2C-01	2.733	2.813	2.972	2.95%	2.753	2.827	2.972	2.67%
UI-2C-02	2.712	2.794	2.954	3.02%	2.758	2.829	2.969	2.57%
UI-2C-03	2.729	2.807	2.961	2.86%	2.753	2.826	2.969	2.65%
UI-2C-04	2.743	2.817	2.964	2.72%	2.756	2.830	2.975	2.67%
UI-2C-05	2.745	2.819	2.964	2.69%	2.753	2.824	2.963	2.58%
UI-2C-06	2.738	2.814	2.963	2.77%	-	-	-	-
UI-2C-07	2.767	2.838	2.977	2.54%	-	-	-	-
UI-2C-08	2.762	2.833	2.972	2.56%	-	-	-	-
Average	**2.741**	**2.817**	**2.966**	**2.76%**	**2.755**	**2.827**	**2.970**	**2.63%**
Std. Dev.	**0.01656**	**0.01301**	**0.00688**	**0.16%**	**0.00206**	**0.00214**	**0.00398**	**0.04%**
COV	**0.60%**	**0.46%**	**0.23%**	**5.84%**	**0.07%**	**0.08%**	**0.13%**	**1.67%**
Range	**0.055**	**0.044**	**0.023**	**0.48%**	**0.005**	**0.006**	**0.012**	**0.10%**
ITD-2C-01	2.785	2.845	2.962	2.20%	2.75	2.819	2.995	2.50%
ITD-2C-02	2.794	2.855	2.974	2.20%	2.749	2.817	2.949	2.50%
ITD-2C-03	2.772	2.836	2.96	2.30%	2.769	2.826	2.936	2.10%
ITD-2C-04	2.772	2.844	2.987	2.60%	2.748	2.816	2.946	2.40%
Average	**2.781**	**2.845**	**2.971**	**2.33%**	**2.754**	**2.82**	**2.957**	**2.38%**
Std. Dev.	**0.00931**	**0.00675**	**0.01080**	**0.16%**	**0.00869**	**0.00391**	**0.02274**	**0.16%**
COV	**0.33%**	**0.24%**	**0.36%**	**7.04%**	**0.32%**	**0.14%**	**0.77%**	**6.89%**
Range	**0.022**	**0.019**	**0.027**	**0.40%**	**0.021**	**0.010**	**0.059**	**0.40%**

Table 5.5 shows the test results of sample 2C, performed at the UI and ITD-Boise lab. The COV for G_{sb} and G_{sa} for UI were all observed to be less than one percent and that for absorption was observed to be about six and two percent for T-84 and IT-144 test methods respectively. Similar was

the case with ITD-Boise lab, except COV for AASHTO T-84 and IT-144 were around seven percent. The D2S limit for UI results for IT-144 satisfied the 0.015 limit for Gsb,Dry whereas, that for AASHTO T-84 of UI and AASHTO T-84 and IT-144 of ITD-Boise results were slightly higher than 0.015. The AASHTO T-84 tests for samples UI-2C-07 and UI-2C-08 were carried out with 16 hours of de-airing and the results obtained were almost identical.

Table 5.6 Round Robin test results for Sample 1D

Sample Designation	T-84				IT-144			
	$G_{sb,Dry}$	$G_{sb,SSD}$	G_{sa}	Abs (%)	$G_{sb,Dry}$	$G_{sb,SSD}$	G_{sa}	Abs (%)
UI-1D-01	2.622	2.660	2.725	1.44%	2.655	2.681	2.724	0.95%
UI-1D-02	2.606	2.644	2.709	1.45%	2.653	2.680	2.726	1.02%
UI-1D-03	2.595	2.637	2.709	1.62%	2.660	2.683	2.722	0.86%
UI-1D-04	2.606	2.640	2.697	1.29%	2.656	2.681	2.725	0.95%
UI-1D-05	2.655	2.683	2.731	1.04%	2.643	2.674	2.726	1.15%
UI-1D-06	2.629	2.665	2.728	1.38%	2.656	2.682	2.727	0.98%
Average	**2.619**	**2.655**	**2.717**	**1.37%**	**2.654**	**2.680**	**2.725**	**0.99%**
Std. Dev.	**0.01966**	**0.01622**	**0.01230**	**0.18%**	**0.00527**	**0.00291**	**0.00163**	**0.09%**
COV	**0.75%**	**0.61%**	**0.45%**	**12.96%**	**0.20%**	**0.11%**	**0.06%**	**8.94%**
Range	**0.060**	**0.046**	**0.034**	**0.58%**	**0.017**	**0.009**	**0.005**	**0.29%**

Table 5.6 shows the test results of sample 2C, performed at the UI lab. The COV for G_{sb} and G_{sa} for UI were all observed to be less than one percent and that for absorption was observed to be about 13 and nine percent for AASHTO T-84 and IT-144 test methods respectively. Omitting the results of UI-1D-01, UI-1D-05, and UI-1D-06 improves the D2S limit of $G_{sb,Dry}$ from 0.060 to 0.011 which is within the assumed acceptable limit of 0.015.

Table 5.7 Round Robin test results for Sample 3E

Sample Designation	T-84				IT-144			
	$G_{sb,Dry}$	$G_{sb,SSD}$	G_{sa}	Abs (%)	$G_{sb,Dry}$	$G_{sb,SSD}$	G_{sa}	Abs (%)
UI-3E-01	2.536	2.565	2.611	1.13%	2.578	2.601	2.638	0.88%
UI-3E-02	2.571	2.595	2.635	0.95%	2.591	2.608	2.637	0.67%
UI-3E-03	2.571	2.598	2.641	1.03%	2.584	2.605	2.639	0.80%
Average	**2.559**	**2.586**	**2.629**	**1.00%**	**2.584**	**2.605**	**2.638**	**0.80%**
Std. Dev.	**0.01650**	**0.01490**	**0.01296**	**0.07%**	**0.00531**	**0.00287**	**0.00082**	**0.09%**
COV	**0.64%**	**0.58%**	**0.49%**	**7.36%**	**0.21%**	**0.11%**	**0.03%**	**10.82%**
Range	**0.035**	**0.033**	**0.030**	**0.18%**	**0.013**	**0.007**	**0.002**	**0.21%**
AW-3E-01	2.561	2.585	2.624	0.94%	2.585	2.603	2.632	0.70%
AW-3E-02	2.564	2.589	2.629	0.95%	-	-	-	-
Average	**2.563**	**2.587**	**2.627**	**0.95%**	**-**	-	-	-
Std. Dev.	**0.00150**	**0.00200**	**0.00250**	**0.00%**	**-**	**-**	**-**	**-**
COV	**0.06%**	**0.08%**	**0.10%**	**0.53%**	**-**	**-**	**-**	**-**
Range	**0.003**	**0.004**	**0.005**	**0.01%**	**-**	**-**	**-**	**-**
ST-3E-01	-	-	-	-	2.589	2.608	2.640	0.75%

Table 5.7 shows the test results of sample 2C, performed at the UI, ALLWEST, and STRATA lab. The COV of G_{sb} and G_{sa} were below one percent for UI test results for AASHTO T-84 and IT-144 test methods whereas, that of absorption were around seven and 11 percent for AASHTO T-84 and IT-144 test methods respectively. The COV were observed to be lower than one percent for specific gravities and absorption for the test results by ALLWEST. The average values of the test results for UI, ALLWEST and STRATA were comparable and had very less differences for both AASHTO T-84 and IT-144 methods.

5.4 Assessment of Round-Robin Experiment

The results in Tables 5.3 to 5.7 for different fine aggregates show that the results from the labs who participated in the "round-robin" experiment are comparable and the results within the labs were very close. The D2S values for the Round Robin experiment ranged from 0.006 to 0.04 for AASHTO T-84 test method and from 0.001 to 0.011 for IT-144 test method. The results were shared with ITD-Boise and it was agreed that UI continue to follow the same procedures for testing 22 aggregates. The results for all aggregate samples tested by UI are presented in Tables 5.9 to 5.23 and a summary is presented in Table 5.24.

5.5 AASHTO T-84 and IT-144 Results

In this section, results are presented for the tested aggregates according to their source districts. Tests were performed on 22 aggregates from five ITD districts in Idaho. A total of 68 AASHTO T-84 tests and 65 IT-144 tests have been run for the data analysis. The tests performed at the University of Idaho (UI), ALLWEST (AW), ITD-Boise (ITD), and STRATA (ST) for the five ITD Districts are discussed in this section. Table 5.8 summarizes the number of tests completed by UI, ALLWEST, ITD (Boise), and STRATA on the 22 aggregates.

A summary of the results for each ITD District are presented in two tables, one for AASHTO T-84 results, and the other for the IT-144 results. These are followed by the average specific gravities and the absorption values, as used for the statistical analysis.

In these tables, the sample identifier code, such as UI-1N-01, refers to aggregate number 1N (i.e. District 1, aggregate N, as shown in Table 3.1 earlier) and the final two numbers report the sample number. The prefix consisting of UI, AW, ST, or ITD refers to the organization which performed the test, so for the result labeled as "UI-1N-01", it implies that the test was performed by the University of Idaho (UI) on the first 4 kg sample taken from aggregate 1N. Abbreviations used for the other contributing organizations are: AW for ALLWEST, ST for STRATA, and ITD for the ITD (Boise) lab.

As these results will be used for the regression analyses discussed in Chapter 6, it is important that the quality of the data be examined carefully. This involves checking the intra-lab results for variability, and possibly repeating tests if the variability is excessive. For this project, the intra-lab variability (d2s) was assessed by calculating the range of the Bulk Specific Gravity ($G_{sb,Dry}$) results. A d2s limit of 0.015 was adopted for this study, which is 0.6 percent of the average $G_{sb,Dry}$ value of all 22 aggregates. If this calculated d2s value was less than 0.015, the variability was deemed acceptable. If the d2s exceeded 0.015, additional testing was performed and the outliers omitted from the data set for that particular aggregate. The acceptable results were averaged for further evaluation.

To further assess the quality of the averaged test data, the averages were compared with results from tests performed by ALLWEST, and others, if available. This inter-lab comparison is reported as the difference between the average of the multiple tests performed by UI with the consultant's single test. The maximum difference, D2S, was again limited to 0.015 for acceptance.

In the summary tables for each District, the right column notes the d2s (intra-lab) and the D2S (inter-lab) values. If these values exceed 0.015 for any aggregate sample, a comment suggesting "possible" further testing is provided for information only.

Table 5.8 Total number of tests run by UI, ITD-Boise, AW and STRATA

Sample Identifiers		AASHTO T-84 Tests				Idaho IT-144 Tests			
UI - ID	ITD - ID	UI	ITD	AW	STRATA	UI	ITD	AW	STRATA
1P	Kt-215c	2	-	1	-	3	-	1	-
1D	Kt-213c	6	-	2	2	7	-	2	1
1N	Kt-222c	3	-	2	-	3	-	1	-
2V	NP-82c	2	-	1	-	2	-	2	-
2Q	Id-256c	2	-	1	-	2	-	2	-
2T	WCW-18c	2	-	2	-	2	-	1	-
2C	WCW-23c	8	4	-	-	5	4	-	-
3H	Ad-161C	3	-	1	-	2	-	1	-
3J	Cn-140c	2	-	1	-	2	-	2	-
3E	Ad-182c	3	-	2	-	3	-	2	-
3A	Ad-136	5	-	1	-	4	-	1	-
5R	Bk-100-c	2	-	1	-	3	-	1	-
5U	Bl-93-s	3	-	1	-	3	-	1	-
5S	Bg-107-c	3	-	1	-	3	-	1	-
5O	Bg-111-c	2	-	1	-	2	-	1	-
6K	Bn-156-c	2	-	1	-	2	-	1	-
6I	Bn-59-s	2	-	1	-	3	-	1	-
6M	Cl-56-s	2	-	2	-	2	-	1	-
6G	Cu-75-s	3	-	1	-	2	-	2	-
6L	Le-160-c	3	-	1	-	3	-	2	-
6F	Le-96-s	3	-	2	-	3	-	1	-
6B	Fr-104-c	5	4	-	-	4	4	-	-
Total		68	8	26	2	65	8	27	1

5.5.1 Results from ITD District 1

The AASHTO T-84 and IT-144 results for the three aggregates supplied by ITD District 1 are summarized in Tables 5.9 and 5.10 respectively. The d2s requirements are met for all samples except the AW T-84 results for Sample 1D. The d2s limit for Sample 1D ranges from 0.001 (STRATA) to 0.025 (AW) for AASHTO T-84. Similarly, the D2S limit for AASHTO T-84 method for Sample 1D ranged from 0.007 (UI and STRATA) to 0.020 (UI and AW). Although, the D2S limit was exceeded for Sample 1D, further testing was not feasible.

Table 5.9 AASHTO T-84 test method results for ITD District 1 aggregates

Sample Designation	**Specific Gravity**			**Absorption (%)**	**Comments**
	DRY	**SSD**	**Apparent**		
UI-1N-01	2.653	2.679	2.723	0.97%	d2s (UI) = 0.003 d2s (AW) = 0.014 D2S = 0.008 **ACCEPT**
UI-1N-02	2.656	2.684	2.732	1.05%	
UI-1N-03	2.653	2.682	2.732	1.09%	
Average	**2.650**	**2.680**	**2.730**	**1.03%**	
Std. Dev.	**0.0014**	**0.0021**	**0.0042**	**0.05%**	
AW-1N-01	2.635	2.668	2.725	1.26%	
AW-1N-02	2.649	2.674	2.717	0.96%	
Average	**2.642**	**2.671**	**2.721**	**1.11%**	
UI-1D-01	2.622	2.660	2.725	1.44%	T-84 (UI) Omit 1,5,6; d2s = 0.011 T-84 (AW) d2s = 0.025 D2S (UI & AW) = 0.020; T-84 (ST) d2s = 0.001 D2S (UI & ST) = 0.007
UI-1D-02	2.606	2.644	2.709	1.45%	
UI-1D-03	2.595	2.637	2.709	1.62%	
UI-1D-04	2.606	2.640	2.697	1.29%	
UI-1D-05	2.655	2.683	2.731	1.04%	
UI-1D-06	2.629	2.665	2.728	1.38%	
Average	**2.603**	**2.640**	**2.705**	**1.46%**	
Std. Dev.	**0.0148**	**0.0122**	**0.0099**	**0.14%**	
AW-1D-01	2.610	2.652	2.724	1.60%	
AW-1D-02	2.635	2.664	2.714	1.11%	
Average	**2.623**	**2.658**	**2.719**	**1.36%**	

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	SSD	Apparent		
Std. Dev.	**0.0125**	**0.0060**	**0.0050**	**0.25%**	D2S (AW & ST) = 0.013 **ACCEPT**
ST-1D-01	2.610	2.654	2.731	1.70%	
ST-1D-02	2.609	2.653	2.729	1.70%	
Average	**2.610**	**2.654**	**2.730**	**1.70%**	
Std. Dev.	**0.0005**	**0.0005**	**0.0010**	**0.00%**	
UI-1P-01	2.634	2.664	2.717	1.15%	d2s = 0.004 D2S = 0.002 **ACCEPT**
UI-1P-02	2.638	2.670	2.827	1.20%	
Average	**2.636**	**2.667**	**2.772**	**1.18%**	
Std. Dev.	**0.0020**	**0.0030**	**0.0550**	**0.03%**	
AW-1P-01	2.634	2.663	2.712	1.09%	

Table 5.10 IT-144 test method results for ITD District 1 aggregates.

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	SSD	Apparent		
UI-1N-01	2.685	2.699	2.722	0.51%	d2s = 0.007 D2S = 0.008 **ACCEPT**
UI-1N-02	2.688	2.702	2.726	0.52%	
UI-1N-03	2.681	2.696	2.722	0.57%	
Average	**2.685**	**2.699**	**2.723**	**0.54%**	
Std. Dev.	**0.0029**	**0.0024**	**0.0019**	**0.026%**	
AW-1N-01	2.677	2.691	2.715	0.52%	
UI-1D-01	2.655	2.681	2.724	0.95%	IT-144 (UI) d2s = 0.017 IT-144 (AW) d2s = 0.055 D2S (UI & AW) = 0.005 IT-144 (ST) d2s = NA D2S (UI & ST) = 0.006 D2S (AW & ST) = 0.001
UI-1D-02	2.653	2.680	2.726	1.02%	
UI-1D-03	2.660	2.683	2.722	0.86%	
UI-1D-04	2.656	2.681	2.725	0.95%	
UI-1D-05	2.643	2.674	2.726	1.15%	
UI-1D-06	2.656	2.682	2.727	0.98%	
UI-1D-07	2.647	2.677	2.730	1.16%	
Average	**2.653**	**2.680**	**2.726**	**1.01%**	
Std. Dev.	**0.0095**	**0.0046**	**0.0042**	**0.188%**	
AW-1D-01	2.620	2.656	2.719	1.39%	
AW-1D-02	2.675	2.692	2.722	0.65%	
Average	**2.648**	**2.674**	**2.721**	**1.02%**	
Std. Dev.	**0.0275**	**0.0180**	**0.0015**	**0.370%**	
ST-1D-01	2.647	2.675	2.723	1.05%	
UI-1P-01	2.612	2.651	2.717	1.49%	Omit 2; d2s = 0.008 D2S = 0.001 **ACCEPT**
UI-1P-02	2.632	2.660	2.707	1.05%	
UI-1P-03	2.620	2.657	2.722	1.43%	
Average	**2.616**	**2.654**	**2.720**	**1.46%**	
Std. Dev.	**0.0040**	**0.0030**	**0.0025**	**0.030%**	
AW-1P-01	2.617	2.660	2.737	1.67%	

The results for IT-144 method are presented in Table 5.10. The d2s values for all the aggregate samples except for Sample 1D were below the 0.015 limit. The D2S values were all within the limit. Although, the d2s exceeded for Sample 1D, further testing was not feasible.

5.5.2 Results from ITD District 2

The AASHTO T-84 and IT-144 results for the four aggregates supplied by ITD District 2 are summarized in Tables 5.11 and 5.12 respectively. For Sample 2C, the d2s limit is exceeded if all eight results are considered for comparison. However, by omitting the six results highlighted in gray, the d2s limit is satisfied for the aggregate Sample 2C. The D2S evaluation between the average results from the different labs is satisfied for Sample 2C, 2Q, and 2V. Although, the D2S for sample 2T was 0.021, which exceeds limit, further testing was not feasible.

The results for IT-144 method are presented in Table 5.12. The d2s values for the aggregate samples were below the 0.015 limit for UI and Boise whereas it was 0.161 for AW for sample 2Q. The D2S value of only sample 2C was within the limit. Although, the D2S limit was exceeded, further testing was not feasible.

Table 5.11 AASHTO T-84 test method results for ITD District 2 aggregates

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	SSD	Apparent		
UI-2C-01	2.733	2.813	2.972	2.95%	T-84 (UI) Omit 1-6, old tests; d2s = 0.005 T-84 (ITD-Boise) Omit 2; d2s = 0.013 D2S = 0.011 **ACCEPT**
UI-2C-02	2.712	2.794	2.954	3.02%	
UI-2C-03	2.729	2.807	2.961	2.86%	
UI-2C-04	2.743	2.817	2.964	2.72%	
UI-2C-05	2.745	2.819	2.964	2.69%	
UI-2C-06	2.738	2.814	2.963	2.77%	
UI-2C-07	2.767	2.838	2.977	2.54%	
UI-2C-08	2.762	2.833	2.972	2.56%	
Average	**2.765**	**2.835**	**2.974**	**2.55%**	
Std. Dev.	**0.0027**	**0.0023**	**0.0024**	**0.008%**	
ITD-2C-01	2.785	2.845	2.962	2.20%	
ITD-2C-02	2.794	2.855	2.974	2.20%	
ITD-2C-03	2.772	2.836	2.960	2.30%	
ITD-2C-04	2.772	2.844	2.987	2.60%	
Average	**2.776**	**2.842**	**2.970**	**2.37%**	
Std. Dev.	**0.0061**	**0.0040**	**0.0123**	**0.170%**	
UI-2Q-01	2.657	2.724	2.848	2.53%	d2s = 0.004 D2S = 0.015 **ACCEPT**
UI-2Q-02	2.661	2.731	2.862	2.65%	
Average	**2.659**	**2.728**	**2.855**	**2.59%**	
Std. Dev.	**0.0019**	**0.0036**	**0.0071**	**0.060%**	
AW-2Q-01	2.644	2.717	2.852	2.76%	
UI-2T-01	2.768	2.846	3.001	2.80%	d2s (UI) = 0.006 d2s (AW) = 0.03 D2S = 0.021
UI-2T-02	2.774	2.847	2.991	2.62%	
Average	**2.771**	**2.846**	**2.996**	**2.71%**	
Std. Dev.	**0.0029**	**0.0004**	**0.0049**	**0.093%**	
AW-2T-01	2.735	2.815	2.974	2.94%	

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	SSD	Apparent		
AW-2T-02	2.765	2.833	2.966	2.46%	
Average	**2.750**	**2.824**	**2.970**	**2.70%**	
UI-2V-01	2.771	2.838	2.972	2.44%	d2s = 0.002 D2S = 0.000 **ACCEPT**
UI-2V-02	2.769	2.837	2.970	2.45%	
Average	**2.770**	**2.838**	**2.971**	**2.45%**	
Std. Dev.	**0.0008**	**0.0008**	**0.0008**	**0.002%**	
AW-2V-01	2.770	2.830	2.949	2.20%	

Table 5.12 IT-144 test method results for ITD District 2 aggregates

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	SSD	Apparent		
UI-2C-01	2.753	2.827	2.972	2.67%	IT-144 (UI) d2s = 0.005 IT-144 (ITD-Boise) Omit 3; d2s = 0.002 D2S = 0.006 **ACCEPT**
UI-2C-02	2.758	2.829	2.969	2.57%	
UI-2C-03	2.753	2.826	2.969	2.65%	
UI-2C-04	2.756	2.830	2.975	2.67%	
UI-2C-05	2.753	2.824	2.963	2.58%	
Average	**2.755**	**2.827**	**2.970**	**2.63%**	
Std. Dev.	**0.0021**	**0.0021**	**0.0040**	**0.046%**	
ITD-2C-01	2.750	2.819	2.995	2.50%	
ITD-2C-02	2.749	2.817	2.949	2.50%	
ITD-2C-03	2.769	2.826	2.936	2.10%	
ITD-2C-04	2.748	2.816	2.946	2.40%	
Average	**2.749**	**2.817**	**2.963**	**2.47%**	
Std. Dev.	**0.0008**	**0.0012**	**0.0224**	**0.047%**	
UI-2Q-01	2.711	2.760	2.849	1.79%	d2s (UI) = 0.001 d2s (AW) = 0.161 D2S = 0.053
UI-2Q-02	2.712	2.763	2.856	1.85%	
Average	**2.712**	**2.762**	**2.853**	**1.82%**	
Std. Dev.	**0.0005**	**0.0015**	**0.0035**	**0.030%**	
AW-2Q-01	2.578	2.668	2.833	3.48%	
AW-2Q-02	2.739	2.752	2.778	0.53%	
Average	**2.659**	**2.710**	**2.806**	**2.01%**	
UI-2T-01	2.801	2.851	2.950	1.81%	d2s = 0.001 D2S = 0.023
UI-2T-02	2.802	2.857	2.964	1.95%	
Average	**2.802**	**2.854**	**2.957**	**1.88%**	
Std. Dev.	**0.0005**	**0.0030**	**0.0070**	**0.068%**	
AW-2T-01	2.825	2.866	2.945	1.45%	

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	SSD	Apparent		
UI-2V-01	2.843	2.867	2.914	0.87%	d2s (UI) = 0.006 d2s (AW) = 0.015 D2S = 0.052
UI-2V-02	2.849	2.873	2.919	0.84%	
Average	**2.846**	**2.870**	**2.917**	**0.85%**	
Std. Dev.	**0.0030**	**0.0030**	**0.0025**	**0.015%**	
AW-2V-01	2.801	2.843	2.923	1.49%	
AW-2V-02	2.786	2.834	2.926	1.72%	
Average	**2.794**	**2.839**	**2.925**	**1.61%**	

5.5.3 Results from ITD District 3

The AASHTO T-84 and IT-144 results for the four aggregates supplied by ITD District 3 are summarized in Tables 5.13 and 5.14. For samples 3H, 3A, and 3E, the d2s limit is exceeded if all results are considered for comparison. However, by omitting the results highlighted in gray, the d2s limit is satisfied for the aggregate sample except 3A, as shown in Table 5.13 for AASHTO T-84 method. The D2S evaluation between the average results from the different labs is satisfied for all the samples. The d2s values ranged from 0.01 to 0.016. Although, the d2s value exceeded the limit, further testing was not feasible.

The results for IT-144 method have been presented in Table 5.14. The d2s values for the aggregate samples were below the 0.015 limit except for AW for sample 3J. The D2S value of all the samples except 3J was within the limit. The d2s value ranged from 0.003 to 0.026, and the D2S value ranged from 0.003 to 0.018. Although, the d2s and D2S values exceeded the limit, further testing was not feasible.

Table 5.13 AASHTO T-84 test method results for ITD District 3 aggregates

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	SSD	Apparent		
UI-3H-01	2.564	2.592	2.637	1.08%	Omit no. 2; d2s = 0.002 D2S = 0.003 **ACCEPT**
UI-3H-02	2.649	2.680	2.735	1.19%	
UI-3H-03	2.566	2.594	2.640	1.10%	
Average	**2.565**	**2.593**	**2.639**	**1.09%**	
Std. Dev.	**0.0010**	**0.0012**	**0.0015**	**0.006%**	
AW-3H-01	2.568	2.596	2.641	1.08%	
UI-3J-01	2.569	2.595	2.638	1.02%	d2s = 0.001 D2S = 0.009 **ACCEPT**
UI-3J-02	2.568	2.598	2.648	1.17%	
Average	**2.568**	**2.597**	**2.643**	**1.10%**	
Std. Dev.	**0.0005**	**0.0014**	**0.0048**	**0.074%**	
AW-3J-01	2.559	2.592	2.647	1.30%	
UI-3A-01	2.578	2.608	2.657	1.16%	Omit 1 and 2; d2s = 0.016 D2S = 0.003
UI-3A-02	2.564	2.596	2.648	1.24%	
UI-3A-03	2.586	2.616	2.666	1.16%	
UI-3A-04	2.581	2.610	2.658	1.12%	
UI-3A-05	2.597	2.623	2.666	1.00%	
Average	**2.588**	**2.616**	**2.663**	**1.09%**	
Std. Dev.	**0.0069**	**0.0056**	**0.0041**	**0.068%**	
AW-3A-01	2.591	2.615	2.653	0.90%	
UI-3E-01	2.536	2.565	2.611	1.13%	T-84 (UI) Omit 1; d2s = 0.000 T-84 (AW) d2s = 0.003 D2S = 0.008 **ACCEPT**
UI-3E-02	2.571	2.595	2.635	0.95%	
UI-3E-03	2.571	2.598	2.641	1.03%	
Average	**2.571**	**2.596**	**2.638**	**0.99%**	
Std. Dev.	**0.0004**	**0.0013**	**0.0029**	**0.036%**	
AW-3E-01	2.561	2.585	2.624	0.94%	
AW-3E-02	2.564	2.589	2.629	0.95%	
Average	**2.563**	**2.587**	**2.627**	**0.95%**	
Std. Dev.	**0.0015**	**0.0020**	**0.0025**	**0.005%**	

Table 5.14 IT-144 test method results for ITD District 3 aggregates

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	SSD	Apparent		
UI-3H-01	2.587	2.604	2.632	0.66%	d2s = 0.004 D2S= 0.008 **ACCEPT**
UI-3H-02	2.591	2.608	2.636	0.66%	
Average	**2.589**	**2.606**	**2.634**	**0.66%**	
Std. Dev.	**0.0020**	**0.0020**	**0.0020**	**0.001%**	
AW-3H-01	2.597	2.613	2.639	0.61%	
UI-3J-01	2.599	2.615	2.643	0.65%	d2s = 0.009 d2s (AW) = 0.026 D2S = 0.018;
UI-3J-02	2.590	2.609	2.639	0.72%	
Average	**2.595**	**2.612**	**2.641**	**0.69%**	
Std. Dev.	**0.0045**	**0.0030**	**0.0020**	**0.037%**	
AW-3J-01	2.564	2.590	2.632	1.01%	
AW-3J-01	2.590	2.610	2.644	0.79%	
Average	**2.577**	**2.600**	**2.638**	**0.90%**	
UI-3A-01	2.589	2.616	2.662	1.07%	d2s = 0.003 D2S = 0.007 **ACCEPT**
UI-3A-02	2.586	2.616	2.665	1.14%	
UI-3A-03	2.589	2.616	2.661	1.05%	
UI-3A-04	2.587	2.615	2.662	1.09%	
Average	**2.588**	**2.616**	**2.663**	**1.08%**	
Std. Dev.	**0.0013**	**0.0004**	**0.0015**	**0.035%**	
AW-3A-01	2.581	2.609	2.657	1.10%	
UI-3E-01	2.578	2.601	2.638	0.88%	IT-144 (UI) d2s = 0.013 IT-144 (AW) d2s = 0.004 D2S = 0.003 **ACCEPT**
UI-3E-02	2.591	2.608	2.637	0.67%	
UI-3E-03	2.584	2.605	2.639	0.80%	
Average	**2.584**	**2.605**	**2.638**	**0.78%**	
Std. Dev.	**0.0053**	**0.0029**	**0.0008**	**0.089%**	
AW-3E-01	2.585	2.603	2.632	0.70%	
AW-3E-02	2.589	2.608	2.640	0.75%	
Average	**2.587**	**2.606**	**2.636**	**0.73%**	
Std. Dev.	**0.0020**	**0.0025**	**0.0040**	**0.025%**	

5.5.4 Results from ITD District 5

The AASHTO T-84 and IT-144 results for the four aggregates supplied by ITD District 5 are summarized in Tables 5.15 and 5.16 respectively. The d2s requirements are met for all the samples as shown in Table 5.15. The D2S evaluation between the average results from the different labs is satisfied for all the samples except for Sample 5S. The D2S values ranged from 0.001 to 0.016. Although, the D2S value exceeded the limit, further testing was not feasible. The low values of d2s suggests that the tests had good repeatability.

The results for IT-144 method have been presented in Table 5.16. The d2s values for all the aggregate samples except for sample 5R were below the 0.015 limit. However, by omitting the results highlighted in gray, the d2s limit is satisfied for the aggregate sample R. The D2S values were all within the limit.

Table 5.15 AASHTO T-84 test method results for ITD District 5 aggregates

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	**SSD**	**Apparent**		
UI-5O-01	2.604	2.620	2.647	0.62%	d2s = 0.012 D2S = 0.009 **ACCEPT**
UI-5O-02	2.616	2.634	2.663	0.66%	
Average	**2.610**	**2.627**	**2.655**	**0.64%**	
Std. Dev.	**0.0063**	**0.0069**	**0.0080**	**0.022%**	
AW-5O-01	2.601	2.618	2.645	0.64%	
UI-5R-01	2.630	2.653	2.694	0.90%	d2s = 0.001 D2S = 0.001 **ACCEPT**
UI-5R-02	2.631	2.654	2.693	0.88%	
Average	**2.630**	**2.654**	**2.693**	**0.89%**	
Std. Dev.	**0.0005**	**0.0002**	**0.0004**	**0.013%**	
AW-5R-01	2.629	2.646	2.673	0.62%	
UI-5S-01	2.604	2.623	2.654	0.73%	d2s = 0.007 D2S = 0.016
UI-5S-02	2.607	2.624	2.653	0.67%	
UI-5S-03	2.611	2.628	2.656	0.65%	
Average	**2.607**	**2.625**	**2.654**	**0.68%**	
Std. Dev.	**0.0027**	**0.0019**	**0.0010**	**0.034%**	
AW-5S-01	2.591	2.613	2.648	0.83%	
UI-5U-01	2.623	2.640	2.667	0.62%	d2s = 0.012 D2S = 0.012 **ACCEPT**
UI-5U-02	2.611	2.629	2.658	0.68%	
UI-5U-03	2.620	2.637	2.665	0.65%	
Average	**2.618**	**2.635**	**2.663**	**0.65%**	
Std. Dev.	**0.0052**	**0.0046**	**0.0037**	**0.025%**	
AW-5U-01	2.606	2.624	2.654	0.70%	

Table 5.16 IT-144 test method results for ITD District 5 aggregates

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	SSD	Apparent		
UI-5O-01	2.613	2.628	2.652	0.55%	d2s = 0.012 D2S = 0.009 **ACCEPT**
UI-5O-02	2.625	2.636	2.655	0.44%	
Average	**2.619**	**2.632**	**2.654**	**0.49%**	
Std. Dev.	**0.0060**	**0.0040**	**0.0015**	**0.058%**	
AW-5O-01	2.610	2.624	2.648	0.55%	
UI-5R-01	2.647	2.662	2.686	0.55%	Omit no. 2; d2s = 0; D2S = 0.008 **ACCEPT**
UI-5R-02	2.664	2.676	2.695	0.44%	
UI-5R-03	2.647	2.661	2.686	0.55%	
Average	**2.647**	**2.662**	**2.686**	**0.55%**	
Std. Dev.	**0.0000**	**0.0005**	**0.0000**	**0.001%**	
AW-5R-01	2.655	2.665	2.682	0.38%	
UI-5S-01	2.612	2.628	2.654	0.60%	d2s = 0.013 D2S = 0.001 **ACCEPT**
UI-5S-02	2.625	2.638	2.658	0.46%	
UI-5S-03	2.612	2.628	2.654	0.60%	
Average	**2.616**	**2.631**	**2.655**	**0.55%**	
Std. Dev.	**0.0061**	**0.0047**	**0.0019**	**0.067%**	
AW-5S-01	2.615	2.628	2.648	0.48%	
UI-5U-01	2.623	2.639	2.664	0.58%	d2s = 0.004 D2S = 0.007 **ACCEPT**
UI-5U-02	2.621	2.636	2.661	0.58%	
UI-5U-03	2.625	2.640	2.663	0.54%	
Average	**2.623**	**2.638**	**2.663**	**0.57%**	
Std. Dev.	**0.0016**	**0.0017**	**0.0012**	**0.019%**	
AW-5U-01	2.616	2.629	2.650	0.49%	

5.5.5 Results from ITD District 6

The AASHTO T-84 and IT-144 results for the seven aggregates supplied by ITD District 6 are summarized in Tables 5.17 and 5.18 respectively. For samples 6G, 6L, and 6B, the d2s limit is exceeded if all results are considered for comparison. However, by omitting the three results highlighted in gray, the d2s limit is satisfied for all aggregate samples except for sample 6M for AW. The d2s value ranged from 0 to 0.027. However, D2S for 6M for AW was within the limit. The D2S evaluation between the average results from the different labs is satisfied for all the samples except 6K, 6B, and 6F. The D2S values for samples 6M and 6B ranged from 0.016 to 0.037. Although, the d2s and D2S values were exceeded, further testing was not feasible.

The results for IT-144 method have been presented in Table 5.18. Omitting the results highlighted in gray, the d2s limit is satisfied for all the aggregate samples except Sample 6G and 6L for AW. The d2s value ranged for Samples 6G and 6L were 0.057 and 0.077 respectively. The D2S values were all within the limit except for aggregate 6F which was 0.019. Although, the d2s and D2S values exceeded the limit, further testing was not feasible.

Table 5.17 AASHTO T-84 test method results for ITD District 6 aggregates

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	SSD	Apparent		
UI-6G-01	2.590	2.631	2.700	1.57%	Omit no.2; d2s = 0.002 D2S = 0.015 **ACCEPT**
UI-6G-02	2.607	2.647	2.716	1.54%	
UI-6G-03	2.588	2.630	2.702	1.63%	
Average	**2.589**	**2.631**	**2.701**	**1.60%**	
Std. Dev.	**0.0014**	**0.0006**	**0.0007**	**0.031%**	
AW-6G-01	2.604	2.638	2.695	1.30%	
UI-6I-01	2.626	2.638	2.659	0.47%	d2s = 0.002 D2S = 0.003 **ACCEPT**
UI-6I-02	2.624	2.637	2.660	0.51%	
Average	**2.625**	**2.638**	**2.659**	**0.49%**	
Std. Dev.	**0.0012**	**0.0006**	**0.0003**	**0.022%**	
AW-6I-01	2.622	2.636	2.658	0.52%	
UI-6F-01	2.650	2.667	2.696	0.64%	d2s (UI) = 0.009 d2s (AW) = 0.002 D2S = 0.027;
UI-6F-02	2.640	2.658	2.689	0.69%	
UI-6F-03	2.641	2.658	2.687	0.65%	
Average	**2.644**	**2.661**	**2.690**	**0.66%**	
Std. Dev.	**0.0045**	**0.0042**	**0.0038**	**0.022%**	
AW-6F-01	2.618	2.643	2.685	0.95%	
AW-6F-02	2.616	2.638	2.676	0.86%	
Average	**2.617**	**2.641**	**2.681**	**0.91%**	
UI-6K-01	2.609	2.627	2.656	0.69%	d2s = 0.003 D2S = 0.016
UI-6K-02	2.612	2.634	2.670	0.83%	
Average	**2.610**	**2.630**	**2.663**	**0.76%**	
Std. Dev.	**0.0017**	**0.0036**	**0.0068**	**0.071%**	
AW-6K-01	2.594	2.618	2.657	0.92%	

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	SSD	Apparent		
UI-6L-01	2.600	2.638	2.704	1.49%	Omit 2; d2s = 0 D2S = 0.015 **ACCEPT**
UI-6L-02	2.355	2.393	2.447	1.59%	
UI-6L-03	2.600	2.640	2.709	1.56%	
Average	**2.600**	**2.639**	**2.707**	**1.52%**	
Std. Dev.	**0.0001**	**0.0010**	**0.0026**	**0.035%**	
AW-6L-01	2.585	2.626	2.695	1.58%	
UI-6B-01	2.381	2.461	2.590	3.40%	
UI-6B-02	2.391	2.472	2.601	3.38%	
UI-6B-03	2.393	2.473	2.599	3.31%	T-84 (UI) Omit 1; d2s = 0.015 T-84 (Boise) Omit 4; d2s = 0.013 D2S = 0.037 NOT GOOD
UI-6B-04	2.387	2.468	2.597	3.39%	
UI-6B-05	2.402	2.479	2.602	3.20%	
Average	**2.393**	**2.473**	**2.600**	**3.32%**	
Std. Dev.	**0.0056**	**0.0040**	**0.0020**	**0.077%**	
ITD-6B-01	2.429	2.503	2.623	3.00%	
ITD-6B-02	2.437	2.512	2.635	3.10%	
ITD-6B-03	2.424	2.497	2.613	3.00%	
ITD-6B-04	2.422	2.494	2.610	3.00%	
Average	**2.430**	**2.504**	**2.624**	**3.03%**	
Std. Dev.	**0.0054**	**0.0062**	**0.0090**	**0.047%**	
UI-6M-01	2.603	2.625	2.662	0.85%	
UI-6M-02	2.604	2.629	2.671	0.96%	
Average	**2.603**	**2.627**	**2.666**	**0.91%**	d2s (UI) = 0.001 d2s (AW) = 0.027 D2S = 0.004
Std. Dev.	**0.0006**	**0.0020**	**0.0045**	**0.055%**	
AW-6M-01	2.585	2.615	2.664	1.14%	
AW-6M-02	2.612	2.628	2.656	0.63%	
Average	**2.599**	**2.622**	**2.660**	**0.89%**	

Table 5.18 IT-144 test method results for ITD District 6 aggregates

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	SSD	Apparent		
UI-6G-01	2.629	2.654	2.697	0.96%	d2s (UI) = 0.005 d2s (AW) = 0.077 D2S = 0.008;
UI-6G-02	2.624	2.651	2.695	1.00%	
Average	**2.627**	**2.653**	**2.696**	**0.98%**	
Std. Dev.	**0.0025**	**0.0015**	**0.0010**	**0.018%**	
AW-6G-01	2.657	2.669	2.688	0.44%	
AW-6G-02	2.580	2.617	2.677	1.41%	
Average	**2.619**	**2.643**	**2.683**	**0.93%**	
UI-6I-01	2.641	2.650	2.664	0.33%	d2s = 0.011 D2S = 0.005 **ACCEPT**
UI-6I-02	2.630	2.643	2.664	0.48%	
UI-6I-03	2.633	2.642	2.657	0.34%	
Average	**2.635**	**2.645**	**2.662**	**0.38%**	
Std. Dev.	**0.0040**	**0.0040**	**0.0035**	**0.008%**	
AW-6I-01	2.630	2.636	2.646	0.23%	
UI-6F-01	2.629	2.647	2.678	0.70%	d2s = 0.009 D2S = 0.019
UI-6F-02	2.636	2.654	2.686	0.71%	
UI-6F-03	2.627	2.647	2.680	0.76%	
Average	**2.631**	**2.649**	**2.681**	**0.72%**	
Std. Dev.	**0.0039**	**0.0033**	**0.0034**	**0.025%**	
AW-6F-01	2.650	2.661	2.681	0.44%	
UI-6K-01	2.626	2.637	2.655	0.41%	d2s = 0.007 D2S = 0.015 **ACCEPT**
UI-6K-02	2.619	2.634	2.660	0.59%	
Average	**2.623**	**2.636**	**2.658**	**0.50%**	
Std. Dev.	**0.0035**	**0.0015**	**0.0025**	**0.088%**	
AW-6K-01	2.638	2.646	2.659	0.30%	

Sample Designation	Specific Gravity			Absorption (%)	Comments
	DRY	SSD	Apparent		
UI-6L-01	2.590	2.622	2.675	1.22%	Omit 1; d2s (UI) = 0 d2s (AW) = 0.057 D2S = 0.014
UI-6L-02	2.566	2.609	2.681	1.67%	
UI-6L-03	2.566	2.612	2.690	1.79%	
Average	**2.566**	**2.611**	**2.686**	**1.73%**	
Std. Dev.	**0.0000**	**0.0015**	**0.0045**	**0.057%**	
AW-6L-01	2.523	2.582	2.681	2.34%	
AW-6L-02	2.580	2.617	2.677	1.41%	
Average	**2.552**	**2.600**	**2.679**	**1.88%**	
UI-6B-01	2.441	2.504	2.603	2.55%	IT-144 (UI) d2s = 0.005 IT-144 (Boise) Omit 1; d2s = 0.016 D2S = 0.014 **ACCEPT**
UI-6B-02	2.436	2.502	2.607	2.68%	
UI-6B-03	2.441	2.502	2.598	2.47%	
UI-6B-04	2.440	2.503	2.605	2.59%	
Average	**2.441**	**2.503**	**2.602**	**2.53%**	
Std. Dev.	**0.0021**	**0.0008**	**0.0033**	**0.077%**	
ITD-6B-01	2.440	2.501	2.598	2.50%	
ITD-6B-02	2.457	2.509	2.593	2.10%	
ITD-6B-03	2.446	2.502	2.592	2.30%	
ITD-6B-04	2.462	2.514	2.598	2.10%	
Average	**2.455**	**2.508**	**2.594**	**2.17%**	
Std. Dev.	**0.0067**	**0.0049**	**0.0026**	**0.094%**	
UI-6M-01	2.602	2.621	2.654	0.76%	d2s = 0.006 D2S = 0.015 **ACCEPT**
UI-6M-02	2.608	2.631	2.669	0.88%	
Average	**2.605**	**2.626**	**2.662**	**0.82%**	
Std. Dev.	**0.0030**	**0.0050**	**0.0075**	**0.059%**	
AW-6M-01	2.590	2.619	2.666	1.11%	

Table 5.19 Average values of aggregate properties for all ITD Districts

S.N	ITD - ID	Test by	T-84				IT-144			
			DRY	SSD	App.	Abs.	DRY	SSD	App.	Abs.
1	Cu-75s	UI	2.589	2.631	2.701	1.60%	2.627	2.653	2.696	0.98%
		AW	2.604	2.638	2.695	1.30%	2.552	2.600	2.679	1.88%
2	BN-59s	UI	2.625	2.638	2.659	0.49%	2.635	2.645	2.662	0.38%
		AW	2.622	2.636	2.658	0.52%	2.630	2.636	2.646	0.23%
3	Ad -161	UI	2.565	2.593	2.639	1.09%	2.589	2.606	2.634	0.66%
		AW	2.568	2.596	2.641	1.08%	2.597	2.613	2.639	0.61%
4	Le -96s	UI	2.644	2.661	2.690	0.66%	2.631	2.649	2.681	0.72%
		AW	2.617	2.641	2.681	0.91%	2.650	2.661	2.681	0.44%
5	Cn-140c	UI	2.568	2.597	2.643	1.10%	2.595	2.612	2.641	0.69%
		AW	2.559	2.592	2.647	1.30%	2.577	2.600	2.638	0.90%
6	Bn -156c	UI	2.610	2.630	2.663	0.76%	2.623	2.636	2.658	0.50%
		AW	2.594	2.618	2.657	0.92%	2.638	2.646	2.659	0.30%
7	Le -160c	UI	2.600	2.639	2.707	1.52%	2.566	2.611	2.686	1.73%
		AW	2.585	2.626	2.695	1.58%	2.552	2.600	2.679	1.88%
8	KT - 222	UI	2.654	2.681	2.729	1.03%	2.685	2.699	2.723	0.54%
		AW	2.642	2.671	2.721	1.11%	2.677	2.691	2.715	0.52%
9	Ad 136	UI	2.588	2.616	2.663	1.09%	2.588	2.616	2.663	1.08%
		AW	2.591	2.615	2.653	0.90%	2.581	2.609	2.657	1.10%
10	Fr 104c	UI	2.393	2.473	2.600	3.32%	2.440	2.503	2.603	2.57%
		Boise	2.430	2.504	2.624	3.03%	2.455	2.508	2.594	2.17%
11	WCW 23	UI	2.765	2.835	2.974	2.55%	2.755	2.827	2.970	2.63%
		Boise	2.776	2.842	2.970	2.37%	2.749	2.817	2.963	2.47%
12	Kt 213	UI	2.603	2.640	2.705	1.46%	2.653	2.680	2.726	1.01%
		AW	2.623	2.658	2.719	1.36%	2.648	2.674	2.721	1.02%
		STRATA	2.610	2.654	2.730	1.70%	2.647	2.675	2.723	1.05%
13	Ad 182	UI	2.571	2.596	2.638	0.99%	2.584	2.605	2.638	0.78%
		AW	2.563	2.587	2.627	0.95%	2.587	2.606	2.636	0.73%
14	Cl -56s	UI	2.603	2.627	2.666	0.91%	2.605	2.626	2.662	0.82%
		AW	2.599	2.622	2.660	0.89%	2.590	2.619	2.666	1.11%
15	ID -256	UI	2.659	2.728	2.855	2.59%	2.712	2.762	2.853	1.82%
		AW	2.644	2.717	2.852	2.76%	2.659	2.710	2.806	2.01%

S.N	ITD - ID	Test by	T-84				IT-144			
			DRY	**SSD**	**App.**	**Abs.**	**DRY**	**SSD**	**App.**	**Abs.**
16	Kt -215	UI	2.636	2.667	2.772	1.18%	2.616	2.654	2.720	1.46%
		AW	2.634	2.663	2.712	1.09%	2.617	2.660	2.737	1.67%
17	Bg -111c	UI	2.610	2.627	2.655	0.64%	2.619	2.632	2.654	0.49%
		AW	2.601	2.618	2.645	0.64%	2.610	2.624	2.648	0.55%
18	WCW18	UI	2.771	2.846	2.996	2.71%	2.802	2.854	2.957	1.88%
		AW	2.750	2.824	2.970	2.70%	2.825	2.866	2.945	1.45%
19	Bk- 100c	UI	2.630	2.654	2.693	0.89%	2.647	2.662	2.686	0.55%
		AW	2.629	2.646	2.673	0.62%	2.655	2.665	2.682	0.38%
20	Bg-107c	UI	2.607	2.625	2.654	0.68%	2.616	2.631	2.655	0.55%
		AW	2.591	2.613	2.648	0.83%	2.615	2.628	2.648	0.48%
21	Bl -93s	UI	2.618	2.635	2.663	0.65%	2.623	2.638	2.663	0.57%
		AW	2.606	2.624	2.654	0.70%	2.616	2.629	2.650	0.49%
22	Np 82c	UI	2.770	2.838	2.971	2.45%	2.846	2.870	2.917	0.85%
		AW	2.770	2.830	2.949	2.20%	2.794	2.839	2.925	1.61%

Table 5.19 summarizes average of all the test results performed by UI, ALLWEST, ITD-Boise and STRATA. These average values will be used in data analysis which is discussed more in detail in Chapter 6.

CHAPTER 6 ANALYSIS

6.1 Introduction

The AASHTO T-84 procedure is a traditional testing method followed by many DOTs as a standard method to calculate the specific gravities and absorption of the fine aggregates. It takes almost three days to complete one AASHTO T-84 test, which involves sample preparation, testing, drying, and finally obtaining data for the calculations. Idaho IT-144 is a relatively new testing method which involves the use of an automated vacuum chamber known as the CoreLok device. This new method is automated, easier and faster to run, taking around 30 minutes to complete.

ITD prefers to use the IT-144 test method in place of the traditional method to calculate the aggregate properties to save time and resources. To fulfil this objective, a study was performed to correlate Idaho IT-144 test results to AASHTO T-84 test results. This chapter discusses how the AASHTO T-84 and Idaho IT-144 are correlated with each other.

Linear and non-linear regression approaches were followed to develop the best statistical model from collected data. Models were prepared with the effect of a single variable, and a combination of variables. The variables with possible effects on the aggregate properties were introduced and their significance was evaluated before using them in the model. AASHTO T-84 values were selected as dependent variables and IT-144 values and all the other variables were selected as the independent variables. The analysis with a single independent variable is known as simple linear regression and that with two or more independent variables is called multiple regression. The significance of the variables on the model were checked before the model was finalized.

All statistical analyses were performed using SPSS, R, Minitab, and MS Excel. The models developed are discussed in the following sections.

The test results generated by the UI lab are summarized in Table 6.1. This table shows the values for Specific Gravities (SGs) and Absorption of the aggregate samples which are the average values of the tests performed for each sample. These values were used to develop a model and the test results from ITD-Boise, ALLWEST, and STRATA will be used for model validation.

Table 6.1 Summary of UI test results

UI-ID	ITD-ID	T-84				IT-144			
		DRY	SSD	App.	Abs.	DRY	SSD	App.	Abs.
1D	Kt-213-c	2.603	2.640	2.705	1.46%	2.653	2.680	2.726	1.01%
1N	Kt-222-c	2.654	2.681	2.729	1.03%	2.685	2.699	2.723	0.54%
1P	Kt-215-c	2.636	2.667	2.772	1.18%	2.616	2.654	2.720	1.46%
2C	WCW-23-c	2.765	2.835	2.974	2.55%	2.755	2.827	2.970	2.63%
2Q	Id 256-c	2.659	2.728	2.855	2.59%	2.712	2.762	2.853	1.82%
2T	WCW-18-c	2.771	2.846	2.996	2.71%	2.802	2.854	2.957	1.88%
2V	Np-82-c	2.770	2.838	2.971	2.45%	2.846	2.870	2.917	0.85%
3A	Ad-136	2.588	2.616	2.663	1.09%	2.588	2.616	2.663	1.08%
3E	Ad-182-c	2.571	2.596	2.638	0.99%	2.584	2.605	2.638	0.78%
3H	Ad-161-c	2.565	2.593	2.639	1.09%	2.589	2.606	2.634	0.66%
3J	Cn-140-c	2.568	2.597	2.643	1.10%	2.595	2.612	2.641	0.69%
5O	Bg-111-c	2.610	2.627	2.655	0.64%	2.619	2.632	2.654	0.49%
5R	Bk-100-c	2.630	2.654	2.693	0.89%	2.647	2.662	2.686	0.55%
5S	Bg-107-c	2.607	2.625	2.654	0.68%	2.616	2.631	2.655	0.55%
5U	BI-93-s	2.618	2.635	2.663	0.65%	2.623	2.638	2.663	0.57%
6B	Fr-104-c	2.393	2.473	2.600	3.32%	2.440	2.503	2.603	2.57%
6F	Le-96-s	2.644	2.661	2.690	0.66%	2.631	2.649	2.681	0.72%
6G	Cu-75-s	2.589	2.631	2.701	1.60%	2.627	2.653	2.696	0.98%
6I	Bn-59-s	2.625	2.638	2.659	0.49%	2.635	2.645	2.662	0.38%
6K	Bn-156-c	2.610	2.630	2.663	0.76%	2.623	2.636	2.658	0.50%
6L	Le-160-c	2.600	2.639	2.707	1.52%	2.566	2.611	2.686	1.73%
6M	Cl-56-s	2.603	2.627	2.666	0.91%	2.605	2.626	2.662	0.82%

6.2 Regression analysis

A regression analysis was performed to correlate IT-144 test results with the AASHTO T-84 results. In this study, the regression analysis models will be used to predict the values of specific gravities and absorption for AASHTO T-84 test method using the IT-144 results along with other variables as presented in Table 6.6.

Bulk specific gravity (G_{sb}) is one of the most important parameters in the design of Hot Mix Asphalt (HMA) pavement mixtures, as the value is used in the calculation of Voids in Mineral Aggregate (VMA) [3]. Once VMA is calculated, its value is used in the calculation of effective binder volume. Designing HMA mixture content also relies heavily on the water absorption capability of aggregates [4]. Therefore, regression analyses were carried out for $G_{sb,Dry}$ and Absorption values and the models developed are presented next.

6.2.1 Simple Linear Regression

Simple linear regression is a statistical analysis method to study the relationship between two quantitative variables. In a simple linear regression, an independent variable is used to predict a dependent variable. For this study, the independent variables are specific gravities and absorption values from IT-144 tests and the dependent variables are those from the AASHTO T-84 test method. The simple linear regression is discussed for each of the aggregate parameters in detail in the sections below.

6.2.1.1 Correlation of Bulk Specific Gravity (Dry) Results

A total of 22 aggregate samples were tested to determine the bulk specific gravity (Dry) values using AASHTO T-84 and IT-144 test methods. These results were discussed in detail in Chapter 5 and the raw data is included in the Appendix.

A graphical representation of the variation in $G_{sb,Dry}$ values and the difference between the values from two test methods are presented in Figure 6.1. In most of the cases, the AASHTO T-84 test method underestimated the values of $G_{sb,Dry}$ compared to the IT-144 test. A minimum difference between two test methods was 0.0003 and the maximum difference was 0.0762. The $G_{sb,Dry}$ values were higher for the ITD District 2 aggregate samples and the lowest were for ITD District 3.

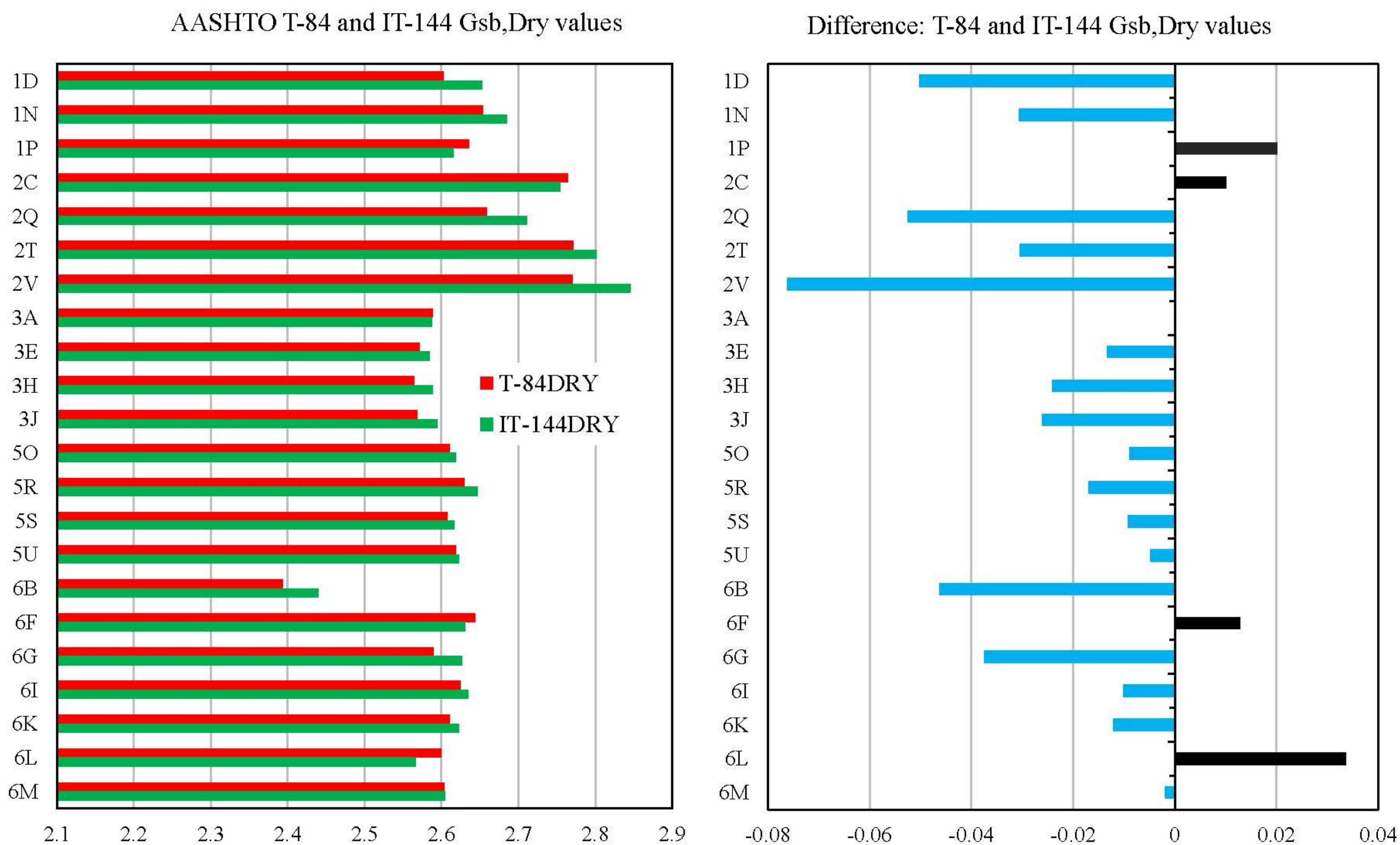


Figure 6.1 Comparison of Gsb,Dry values between AASHTO T-84 and IT-144 test methods

To determine if the set of results from two test methods are significantly different or not, a statistical test called a “paired t-test” was performed. The objective of a paired t-test is to compare population means of two sample sets. Here, the two test methods are AASHTO T-84 and IT-144 and the observation is $G_{sb,Dry}$. The assumptions made for the paired t-test are as follows.

Null Hypothesis, H_0: The difference between the average value of $G_{sb,Dry}$ for AASHTO T-84 and IT-144 is zero.

$$\mu_1 - \mu_2 = 0$$

Alternative Hypothesis, H_a: The difference between the average value of $G_{sb,Dry}$ for AASHTO T-84 and IT-144 is not equal to zero.

$$\mu_1 - \mu_2 \neq 0$$

To test: The difference of the mean between the two test method is statistically significant or not at 95 percent Confidence Interval (CI)

Table 6.2 Paired t–test result on $G_{sb,Dry}$

Number of Samples	22
Degree of Freedom	21
AASHTO T-84 mean	2.622
IT-144 mean	2.639
Mean Difference	0.017
t-statistic	-3.075
p-value	0.00574
Significant Difference	**YES**

The result of the t-test are presented in Table 6.2. A mean difference of 0.017 was observed between the 22 aggregates samples for AASHTO T-84 and IT-144 test results. A p-value of 0.00574 was obtained at 95 percent CI. For p-value $< \alpha = 0.05$, the null hypothesis (H_0) is rejected and if the p-value $> \alpha = 0.05$, H_0 is accepted. As the p-value in the analysis for $G_{sb,Dry}$ is 0.00574 which is less than α-value = 0.05, we reject the null hypothesis in this case, which means, at 95 percent CI, there is a significant difference between the $G_{sb,Dry}$ values obtained by the test methods AASHTO T-84 and IT-144. As there is a significant difference between the two series of tests, regression analysis may be used to develop suitable correlations.

A scatter plot for the UI $G_{sb,Dry}$ test results is shown in the Figure 6.2 with IT-144 values on the horizontal axis and AASHTO T-84 values on the vertical axis. Generally, an R-value from 0.80 to 1.00 is considered a very strong correlation, and an R-value from 0.60 to 0.79 is considered a strong correlation [8]. For our analysis, a Pearson correlation coefficient, R = 0.95 was obtained which is considered a very strong correlation.

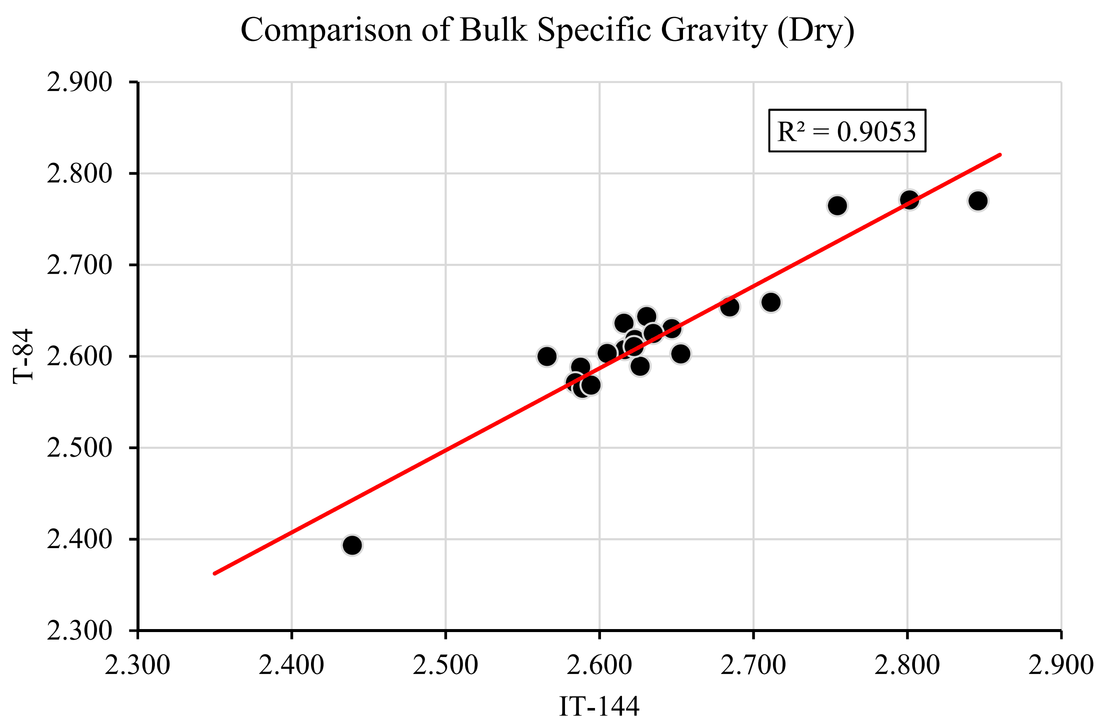


Figure 6.2 Scatter plot of UI $G_{sb,Dry}$ data from IT-144 and AASHTO T-84 tests

6.2.1.1.1 Linear Regression Model with Single Independent Variable

A linear regression model was developed using the $G_{sb,Dry}$ value from AASHTO T-84 as the dependent variable and $G_{sb,Dry}$ from IT-144 as the independent variable. The analysis generated the following model.

$$T84G_{sb,Dry} = 0.2518 + 0.8981 \times IT144G_{sb,Dry} \tag{6.1}$$

For this model, the R^2 and adjusted R^2 values were 90.5 and 90.1 percent, respectively. The model was developed for a range of IT-144 data from $G_{sb,Dry}$ = 2.4 to 2.9.

The analysis also considered logarithmic and power functions for the correlation. These results are summarized in Table 6.3. Upon comparison, we can see that the linear and power trends had the best correlation at R^2 = 90.5 to 90.6 percent.

A linear regression model is considered good, if the following conditions are met:

a. R^2 value is greater than 70 percent,
b. Residuals lie on or very close to the line of equality in the normal probability plot,
c. The residuals are scattered when a graph is plotted with residuals in vertical axis and fitted value in the horizontal axis, and
d. The histogram of the residuals is normally distributed along the mean = 0.

The residual plot and fitted line plot for the model are presented in Figures 6.3 and 6.4. Figure 6.3 shows that the residuals are normally distributed and are scattered. Figure 6.4 shows R^2 = 90.5 percent. The Confidence Interval (CI) and Prediction Interval (PI) lines in Figure 6.4 shows a range of data which are 95 percent certain that it contains the true mean of the population, and 95 percent certain that predicted data will range between the lines. A simple linear model is recommended as the correlations are very close for all the models as shown in Table 6.3, and the model supported all the conditions mentioned above.

A better model with higher R^2 could be developed with a multiple regression model where more than one independent variables are considered in the analysis. The multiple regression analysis is discussed in detail in section 6.2.2.

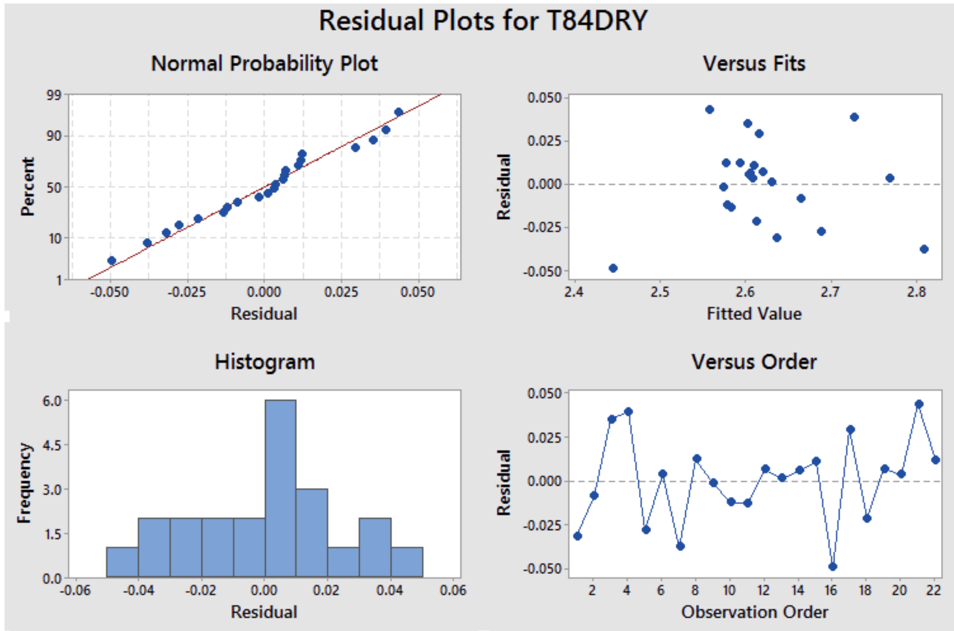


Figure 6.3 Residual plot for simple linear model for $G_{sb,Dry}$

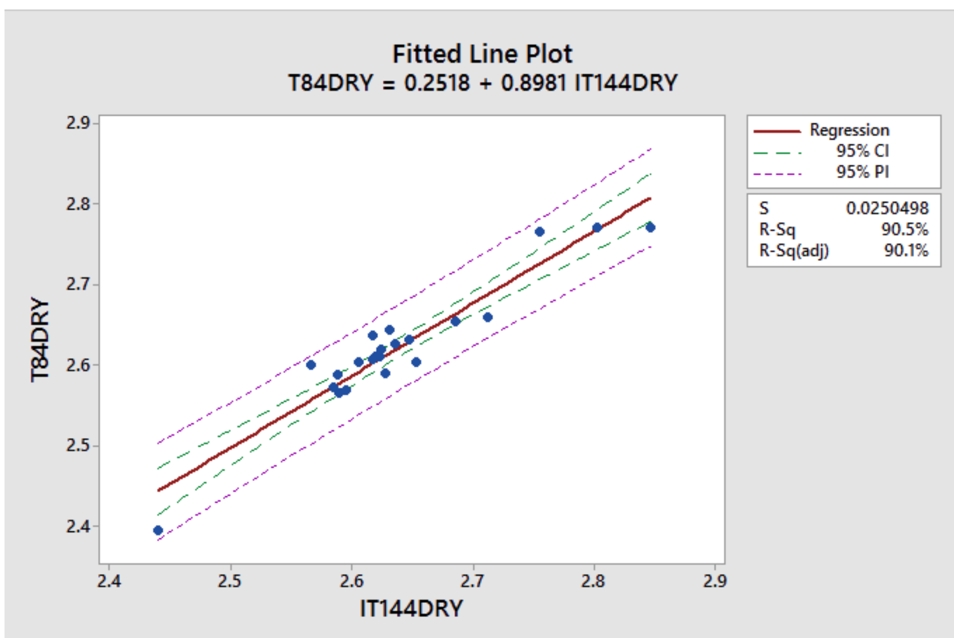


Figure 6.4 Fitted line plot for simple linear model for $G_{sb,Dry}$

Table 6.3 Regression models for $G_{sb,Dry}$

A. Linear model with single independent variable	
$T84G_{sb,Dry} = 0.2518 + 0.8981 \times IT144G_{sb,Dry}$	$R^2 = 90.53\%$
$T84\ G_{sb,Dry} = 2.615\ \ln(IT144\ G_{sb,Dry}) + 0.1194$	$R^2 = 89.75\%$
B. Non-linear model with single independent variable	
$T84\ G_{sb,Dry} = 1.0168(IT144\ G_{sb,Dry})^{0.9894}$	$R^2 = 90.60\%$

6.2.1.2 Correlation of Absorption Results

A total of 22 fine aggregae samples were tested to determine the Absorption values using AASHTO T-84 and IT-144 test methods. These results were discussed in detail in Chapter 5 and the raw data is included in the Appendix.

A graphical representation of the variation in Absorption values and the difference between the values from two methods is presented in Figure 6.5. In most of the cases, AASHTO T-84 test method underestimated the values of Absorption compared to the IT-144 test. Absorption values of 0.49 to 3.32 percent and 0.38 to 2.63 percent were obtained for the AASHTO T-84 and IT-144 test methods, respectively. The minimum difference between two test methods was 0.0072 percent and the maximum difference was 1.6 percent. The Absorption values were higher for the ITD District 2 aggregate samples and the lowest were for ITD District 5.

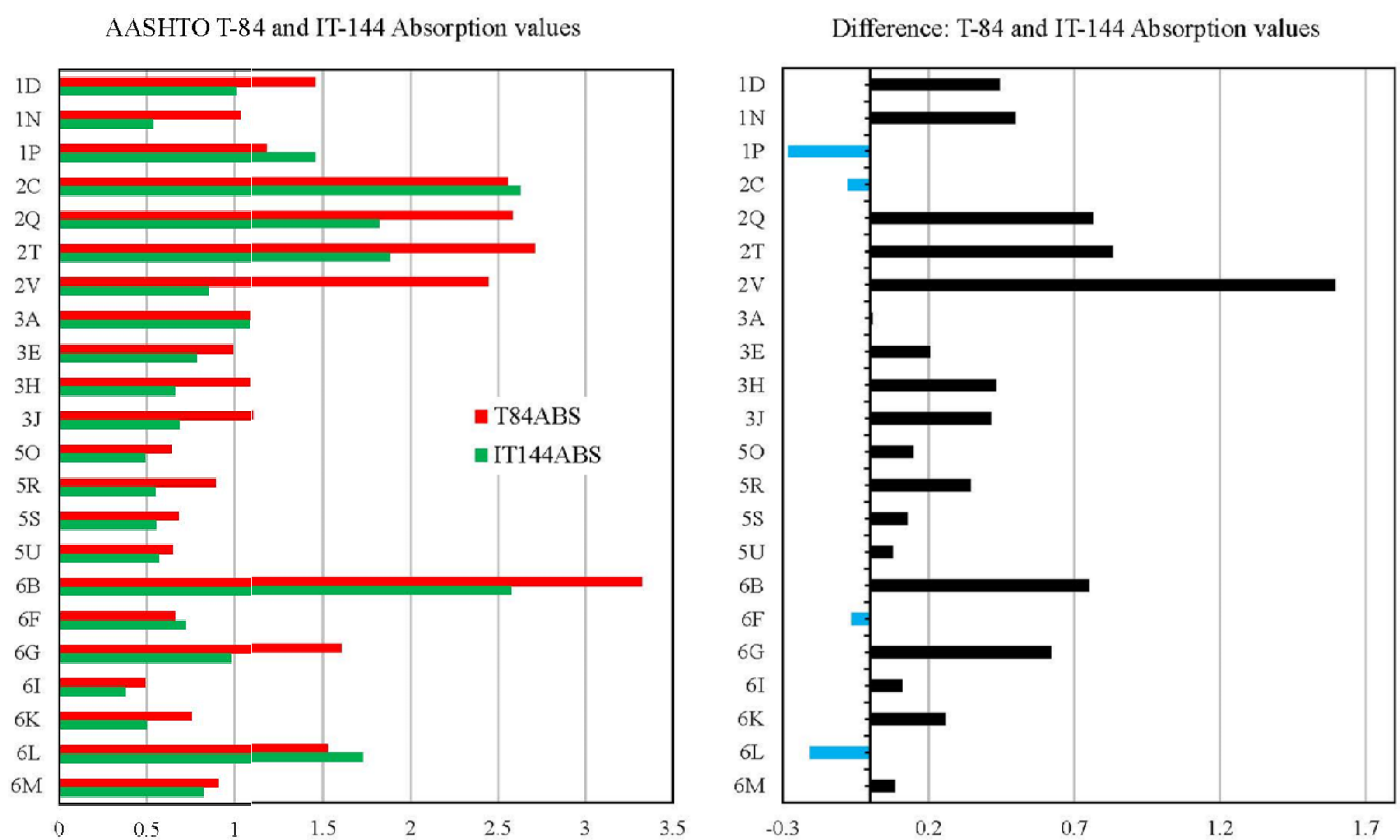


Figure 6.5 Comparison of AASHTO T-84 and IT-144 Absorption values

A paired t-test was used to determine if the set of results from two test methods are significantly different or not. The parameter, Absorption, was observed in two test methods, AASHTO T-84 and IT-144. The assumptions made for the paired t-test are as follows.

Null Hypothesis, H_0: The difference between the average value of Absorption for AASHTO T-84 and IT-144 is zero.

$$\mu_1 - \mu_2 = 0$$

Alternative Hypothesis, H_a: The difference between the average value of Absorption for AASHTO T-84 and IT-144 is not equal to zero.

$$\mu_1 - \mu_2 \neq 0$$

To test: The difference of the mean between the two test method is statistically significant or not at 95 percent Confidence Interval (CI)

Table 6.4 Paired t–test result on Absorption

Number of Samples	22
Degree of Freedom	21
AASHTO T-84 mean	1.38%
IT-144 mean	1.06%
Mean Difference	0.32%
t-statistic	3.589
p-value	0.002
Significance Difference	**YES**

The result of the t-test are presented in Table 6.4. A mean difference of 0.32 percent was observed between the 22 aggregates samples for AASHTO T-84 and IT-144 test results. A p-value of 0.002 was obtained at 95 percent CI. As the p-value in the analysis for Absorption, $\alpha < 0.05$, we reject the null hypothesis in this case, which means, at 95 percent CI, there is a significant difference between the Absorption values obtained by the test methods AASHTO T-84 and IT-144. A regression analysis may be used to develop suitable correlations as there is a significant difference between the two series of tests.

A scatter plot is shown in Figure 6.6 with IT-144 values in the horizontal axis and AASHTO T-84 values in the vertical axis for the Absorption. For our analysis, a Pearson correlation coefficient, R = 0.85 was obtained which is considered a very strong correlation. The red marker in Figure 6.6 shows the data point for Sample 2V. This is considered as an outlier in the data set and was omitted from the statistical analysis. An R^2 = 85 percent was obtained after omitting this data point from the analysis, as shown in Figure 6.7. This resulted in an improved correlation.

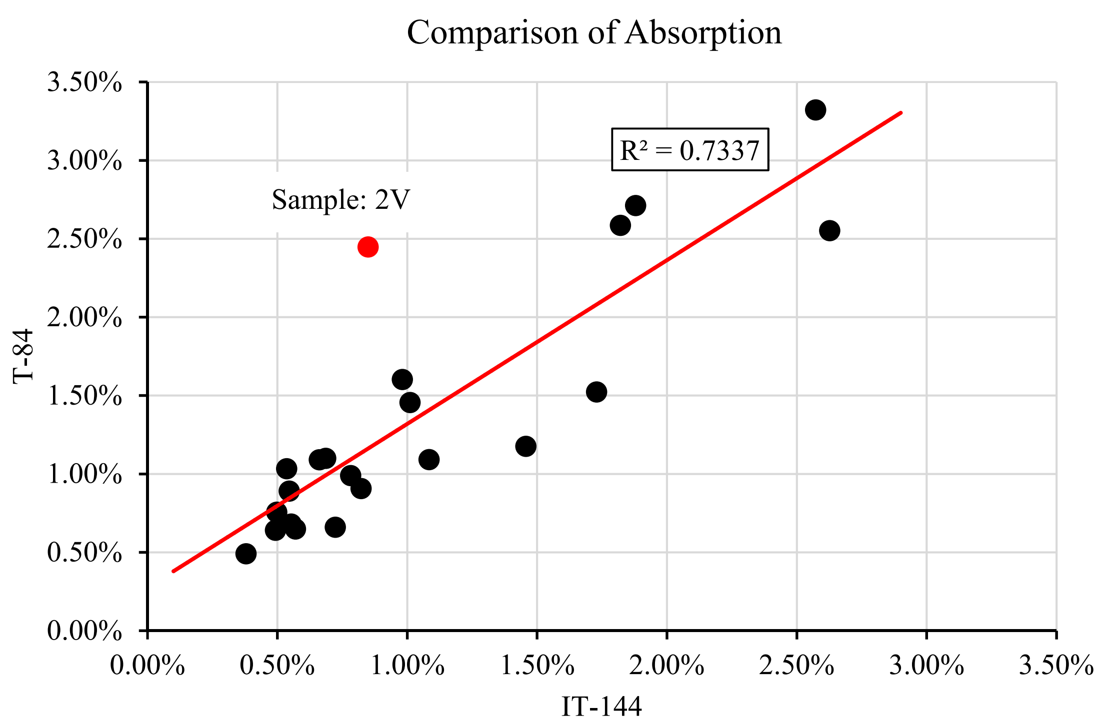


Figure 6.6 Scatter plot of UI Absorption data from IT-144 and AASHTO T-84 tests

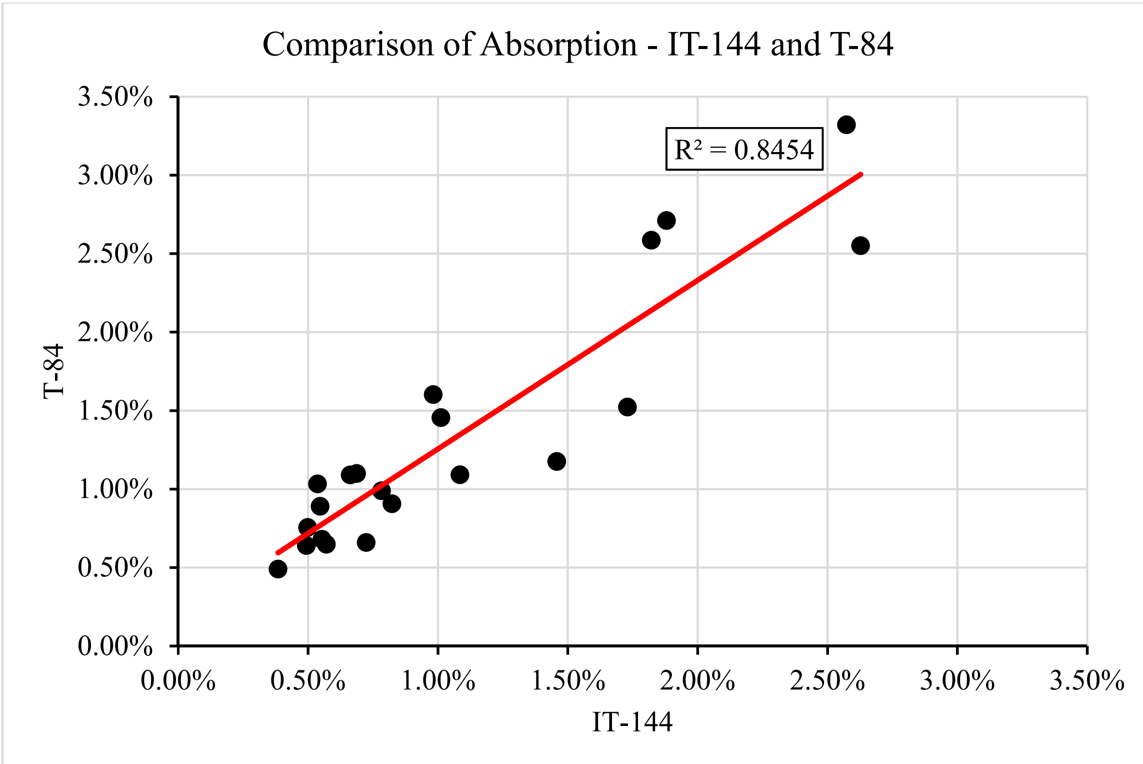


Figure 6.7 Scatter plot of UI Abs. data from IT-144 and AASHTO T-84 tests after omitting outlier

6.2.1.2.1 Linear Regression Model with Single Independent Variable

A linear regression model was developed using the Absorption value from AASHTO T-84 as the dependent variable and Absorption from IT-144 as the independent variable. The analysis generated the following model.

$$T84ABS = 0.1819 + 1.074 \times IT144ABS \qquad (6.2)$$

For this model, the R^2 value was 84.6 percent. The model was developed for IT-144 data where the absorption ranged between between 0.4 and 2.7 percent.

The analysis also considered logarithmic and power functions for the correlation. These results are summarized in Table 6.5. Upon comparison, we can see that the power and linear trends had the best correlation at R^2 = 83.41 to 84.60 percent, respectively.

Table 6.5 Regression model for Absorption

A. Linear model with single independent variable	
$T84ABS = 0.1819 + 1.074 \times IT144ABS$	$R^2 = 84.60\%$
$T84ABS = 0.9084 + 1.1433 \times \ln(IT144ABS)$	$R^2 = 80.42\%$
B. Non-linear model with single independent variable	
$T84ABS = 0.7863 \times IT144\ ABS^{0.9864}$	$R^2 = 83.41\%$

The residual plot and fitted line plot for the linear model is presented in Figures 6.8 and 6.9. The residuals lie very close to the line of equality in the normal probability plot. Also, the histogram of the residuals is normally distributed along the mean of 0. The model developed has an R^2 value greater than 70 percent, which is considered a good correlation.

A better model with higher R^2 could be developed with a multiple regression model where more than one independent variable is considered in the analysis. The multiple regression analysis is discussed in detail in section 6.2.2.

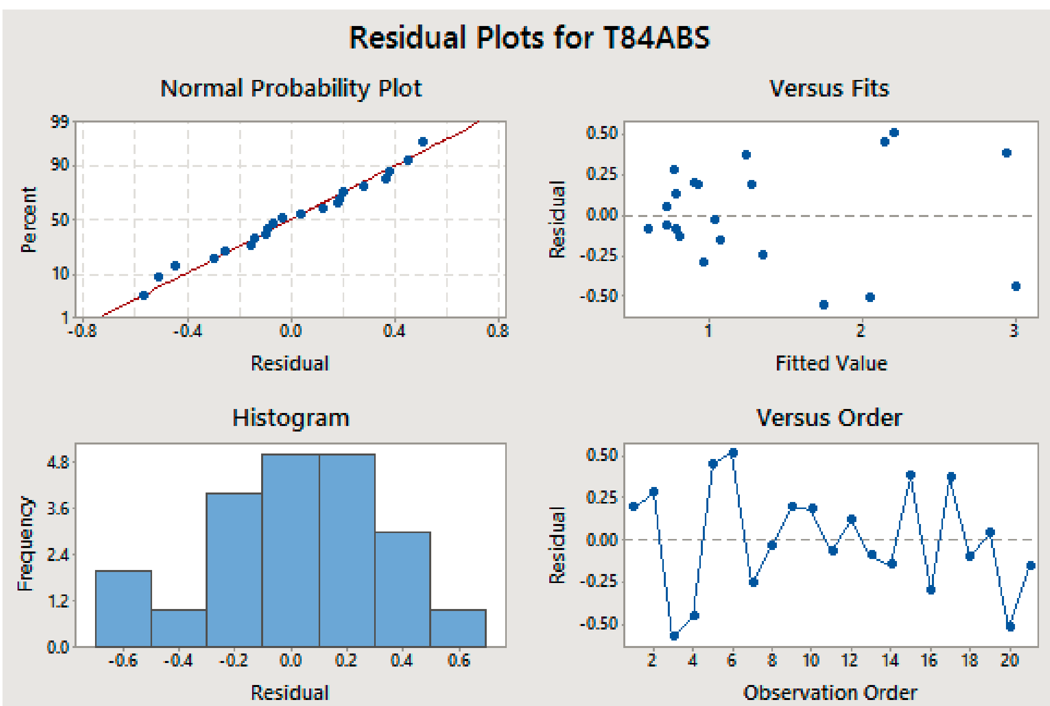


Figure 6.8 Residual plot for simple linear model for Absorption data

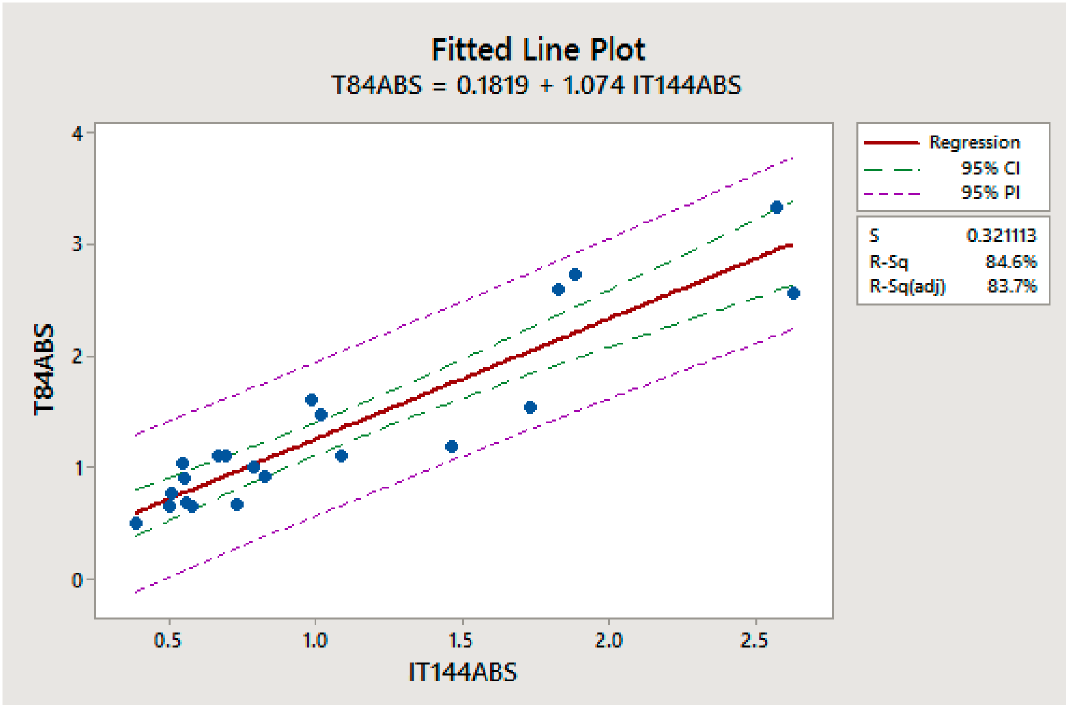


Figure 6.9 Fitted line plot for simple linear model for Absorption data

6.2.1.3 Correlation of Bulk Specific Gravity (SSD) Values

A total of 22 samples were tested to determine the $G_{sb,SSD}$ values using AASHTO T-84 and IT-144 test methods. These results were discussed in detail in Chapter 5 and the raw data is included in the Appendix.

A graphical representation of the variation in $G_{sb,SSD}$ values and difference between the values from two test methods are presented in Figure 6.10. In most of the cases, the IT-144 test method underestimated the values of $G_{sb,SSD}$ than the AASHTO T-84. In comparing the results, the underestimation ranged from 0.003 to 0.4, while for the few overestimated cases, a difference of 0.001 to 0.029 was noted. The $G_{sb,SSD}$ values were higher for the ITD District 2 aggregate samples and the lowest were for ITD District 3.

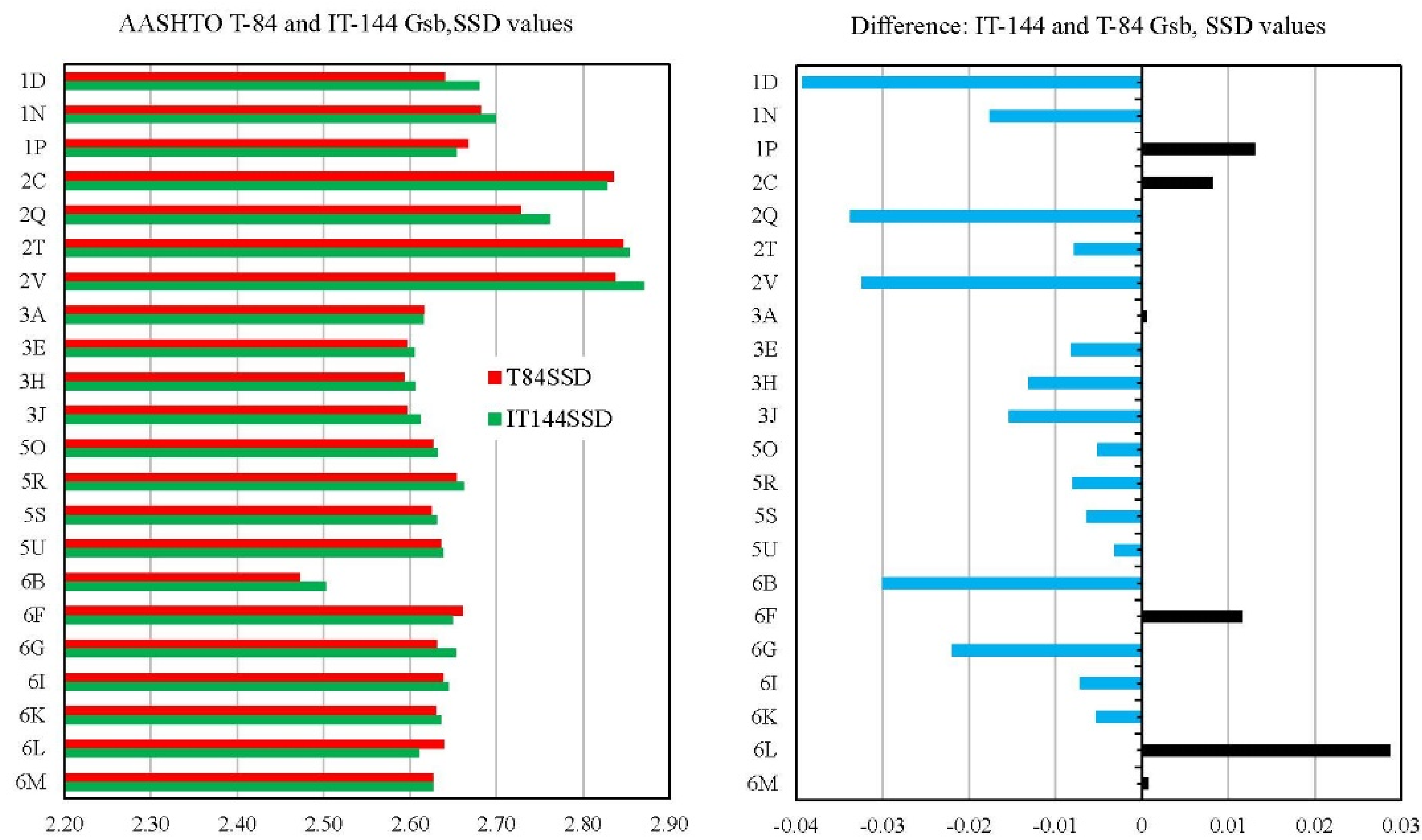


Figure 6.10 Comparison of AASHTO T-84 and IT-144 $G_{sb,SSD}$ values

6.2.1.4 Correlation of Apparent Specific Gravity Results

A total of 22 samples were tested to determine the G_{sa} values using AASHTO T-84 and IT-144 test methods. These results were discussed in detail in Chapter 5 and the raw data is included in the Appendix.

A graphical representation of the variation in G_{sa} values and difference between the values from two test methods are presented in Figure 6.11. In most of the cases, AASHTO T-84 test method underestimated the values of $G_{sb,Dry}$ than the IT-144. A minimum difference between two test methods was 0.0001 and the maximum difference was 0.0547. The $G_{sb,Dry}$ values were higher for the ITD District 2 aggregate samples and the lowest were for ITD District 3.

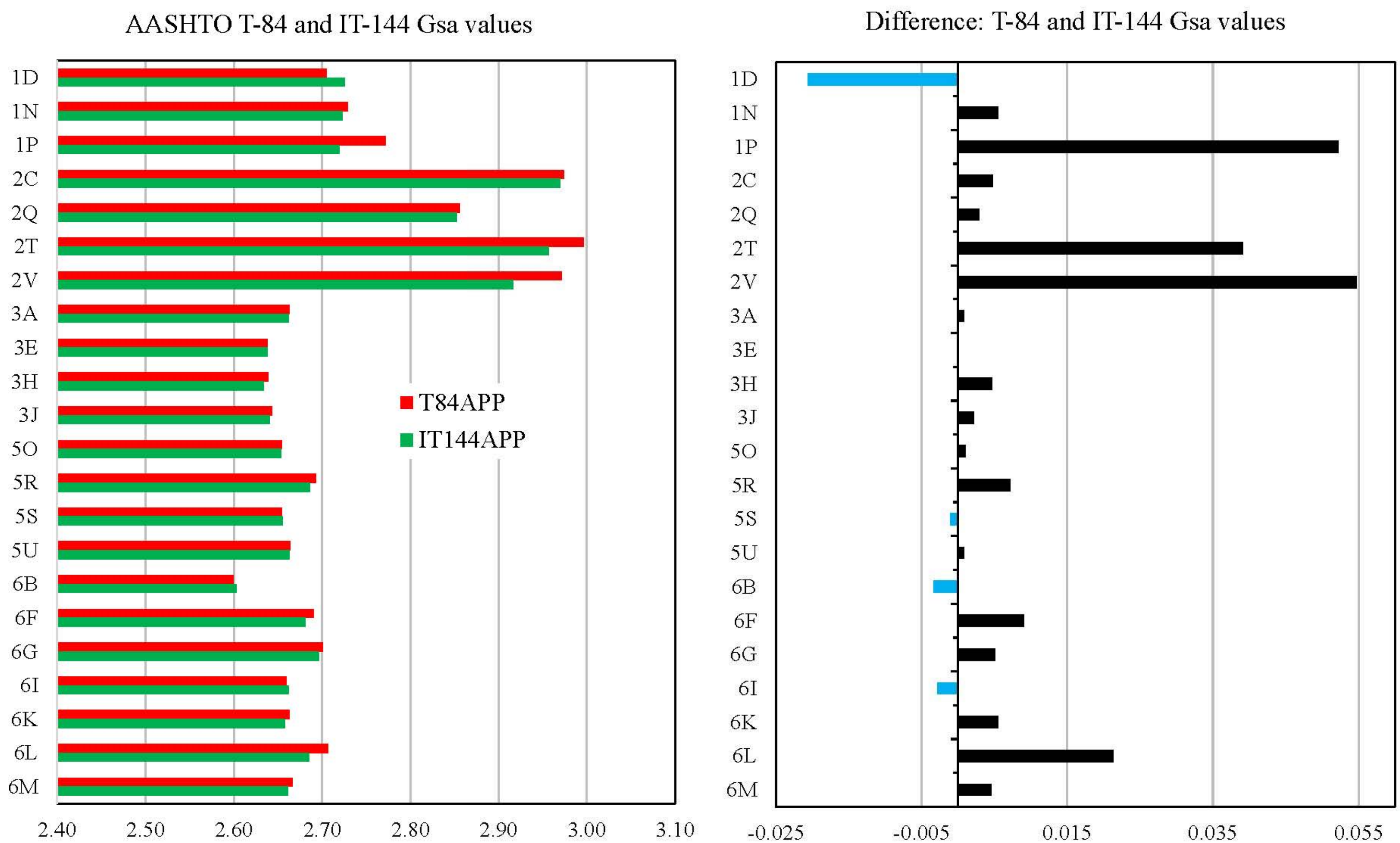


Figure 6.11 Comparison of AASHTO T-84 and IT-144 G_{sa} values

6.2.2 Variables for Multiple Regression Analysis

For the development of a model to correlate results of IT-144 with AASHTO T-84 test methods, parameters like material type, particle sizes, particle shape parameters, and properties of the aggregates like specific surface area (SSA) and fineness modulus (FM) were considered. The values for each of these variables, for the 22 aggregates tested, are presented in Table 6.6.

6.2.2.1 Specific Surface Area

The surface area of the fine aggregate is expected to have a significant effect on the physical properties. The surface area depends on the type, texture, and grain size distribution of the aggregate material [14]. The term "Specific Surface Area" (SSA) refers to the property of the aggregate defined as the surface area of the material per unit mass or bulk volume of the aggregates. This unique value is determined from the grain size distribution.

The value of SSA is higher for finer aggregates and lower for coarser aggregates. The minimum and maximum value of SSA were calculated as 5.31 and 11.13 respectively for the 22 aggregates. Figure 6.12 shows SSA has a negative correlation with the $G_{sb,Dry}$ values for AASHTO T-84 and IT-144 test methods, and was not statistically significant (p-value = 0.498 and 0.345 respectively). Figure 6.12 shows a negative correlation of SSA with Absorption values for AASHTO T-84 and IT-144 test methods.

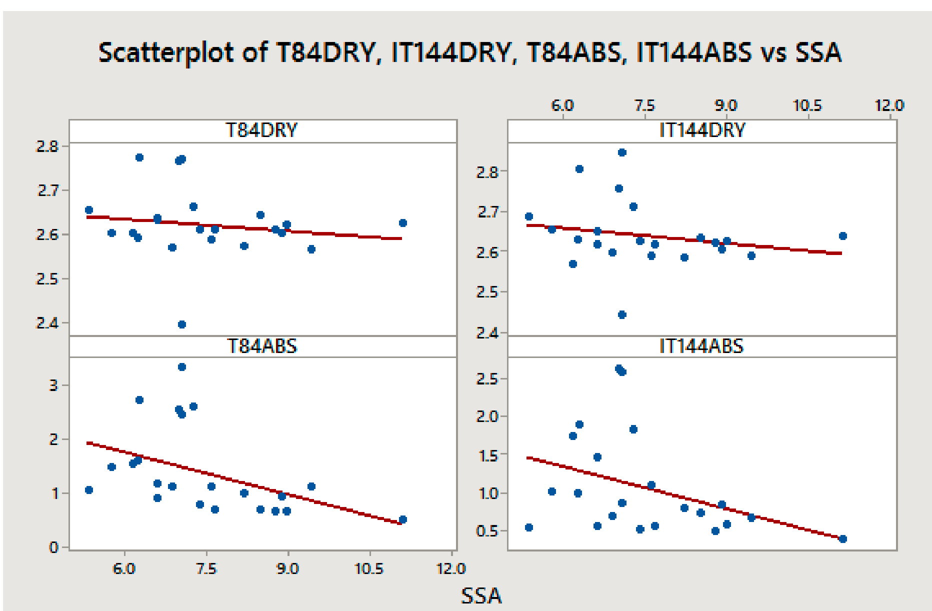


Figure 6.12 Scatter plot of SSA with $G_{sb,Dry}$ and Abs. data for IT-144 & AASHTO T-84 tests

6.2.2.2 Fineness Modulus

Fineness Modulus (FM) is an index which defines the relative sizes of fine and coarse particles in an aggregates. FM is a value obtained by dividing the sum of percentage of aggregates retained in a series of sieves by 100. Sieve sizes No. 4, 8, 16, 30, 50 and 100 are used for the calculation of FM. Generally, the FM of fine aggregate ranges from 2.0 to 4.0 [14].

A smaller value of FM indicates that the sample has more fine aggregate. The value of FM ranged from 3.03 to 4.13 or the samples used in this study. Figure 6.13 shows a positive correlation between FM and Absorption which is statistically significant (p-value = 0.024). The correlation of FM with IT-144 Absorption was not statistically significant (p-value = 0.101).

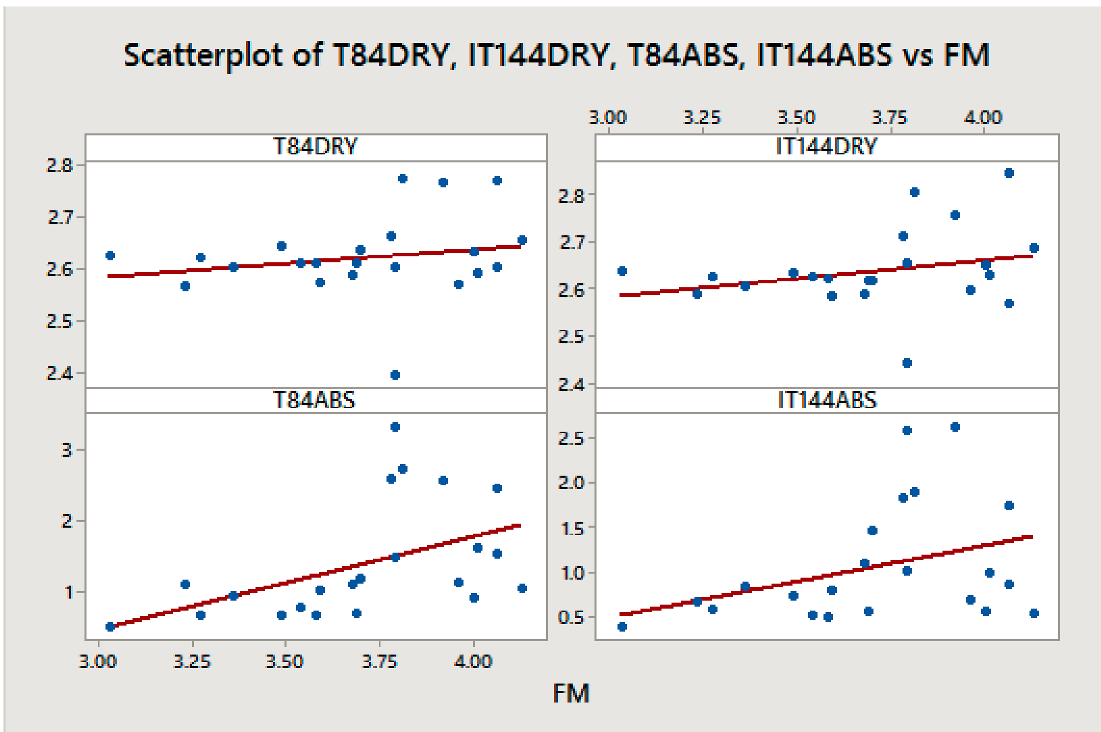


Figure 6.13 Scatter plot of FM with $G_{sb,Dry}$ & Abs. data for IT-144 and AASHTO T-84 test

6.2.2.3 Particle Sizes

Particle size is also likely to affect the outcome of the test methods. The particle sizes are selected from the Grain Size Distribution (GSD) test. GSD curve is plotted with the percent passing data on the vertical axis and particle size in the horizontal axis. In the GSD curve, D_{10} value represents the diameter of particles corresponding to 10 percent finer in the grain size distribution test. D_{10} is also called the effective size. The values for other particle sizes like, D_{30}, D_{50}, and D_{60} were also considered for this study. Figure 6.14 shows that there is a positive correlation between D_{30} and AASHTO T-84 and IT-144 value for $G_{sb,Dry}$ whereas, only IT-144 test value had a significant correlation with D_{30}.

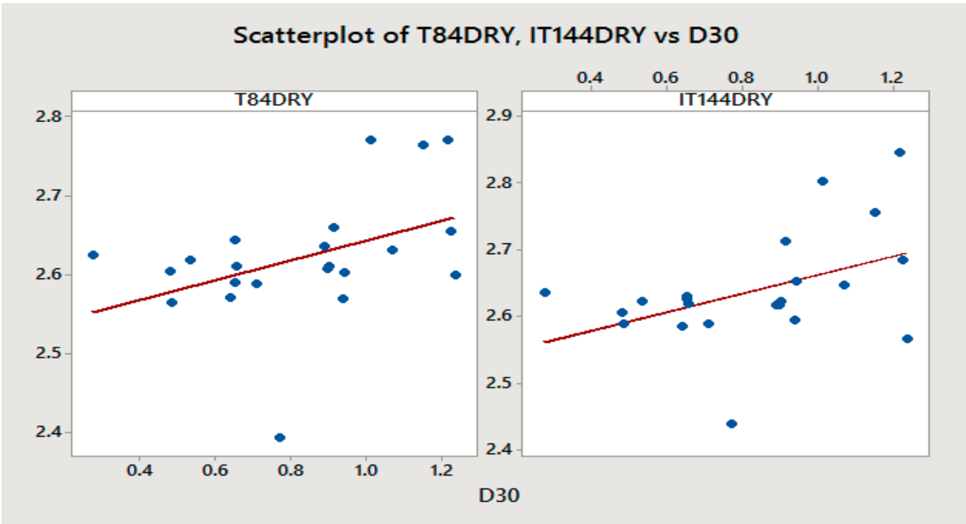


Figure 6.14 Scatter plot of D_{30} with $G_{sb,Dry}$ data for IT-144 and AASHTO T-84 test

The correlation between D_{30} values and AASHTO T-84 and IT-144 $G_{sb,Dry}$ values were statistically significant (p-value = 0.05 and 0.04 respectively). Other particle sizes like D_{10}, D_{50}, and D_{60} did not have any direct correlation with AASHTO T-84 and IT-144 results as shown in Figure 6.15.

6.2.2.4 Coefficient of Uniformity (C_u)

The coefficient of uniformity (C_u) is based on the size distribution of a granular material. C_u is defined by Equation 6.1.

$$C_u = \frac{D_{60}}{D_{10}} \tag{6.1}$$

The C_u of the fine aggregates considered for this study ranged from 10.06 to 47.94. There was a positive correlation between C_u and $G_{sb,Dry}$ values obtained from AASHTO T-84 (p-value = 0.735) and IT-144 (p-value = 0.606) test results, whereas, a negative correlation was obtained between C_u and

Absorption values (p-value = 0.194 for AASHTO T-84 and p-value = 0.115 for IT-144) for both test methods. Neither of the correlations are statistically significant.

6.2.2.5 Coefficient of Curvature

The coefficient of curvature is a parameter which depends on the shape of the GSD curve. Its value is based on three particle sizes and defined by Equation 6.2. For a well graded sand, the value of C_c ranges from one to three.

$$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} \tag{6.2}$$

The C_c of the fine aggregates considered for this study ranged from 0.64 to 4.81. A positive correlation was obtained between the C_c and $G_{sb,Dry}$ (p-values = 0.194 for AASHTO T-84 and p-value of 0.115 for IT-144) and Absorption (p-value = 0.373 for AASHTO T-84 and p-value = 0.547 for IT-144) values. However, the correlations were all statistically insignificant.

6.2.2.6 Material type

A general description of the rock types in the aggregates used for this study were given in Table 3.1. Several grouping of materials were analyzed for possible significant influence, but the correlation was very poor. It is possible that a much bigger sample size may have revealed more information.

6.2.3 Multiple Regression Analysis

A multiple regression analysis was carried out for a better prediction of the dependent variables. The dependent variable was AASHTO T-84 and the independent variables were IT-144, FM, SSA, D_{10}, D_{30}, D_{50}, D_{60}, C_u, and C_c which are presented in Table 6.6. The variables IT-144 value, FM, D_{30}, D_{60}, and C_c were used for the analysis for AASHTO T-84 $G_{sb,Dry}$ prediction, whereas, variables IT-144 values, D_{50}, D_{60}, C_u, and C_c developed a better prediction model for AASHTO T-84 Absorption.

Various models with different combinations were run to obtain an optimum model with the best R^2 value and a normally distributed plot of residuals. The scatter plot of AASHTO T-84 $G_{sb,Dry}$ data and all the variables is presented in Figure 6.15 below. The combinations of independent variables were chosen for trial by examining if the data correlated with the dependent variable (Figures 6.15 and 6.17).

For this study, multiple regression analyses were performed for the Bulk Specific Gravity and Absorption data, which are discussed in detail in the following sections.

Table 6.6 Variables for analysis

UI-ID	ITD-ID	SSA	FM	D_{10}	D_{30}	D_{50}	D_{60}	C_u	C_c
1D	Kt-213c	5.76	3.79	0.062	0.941	2.175	2.972	47.94	4.81
1N	Kt-222c	5.31	4.13	0.130	1.223	2.936	3.911	30.08	2.94
1P	Kt-215c	6.58	3.70	0.143	0.889	1.989	2.730	19.09	2.02
2C	WCW-23c	6.97	3.92	0.285	1.151	2.205	2.868	10.06	1.62
2Q	Id 256c	7.25	3.78	0.138	0.913	2.082	2.903	21.04	2.08
2T	WCW-18c	6.25	3.81	0.083	1.010	2.433	3.180	38.31	3.86
2V	Np-82c	7.04	4.06	0.297	1.214	2.462	3.207	10.80	1.55
3A	Ad-136	7.59	3.68	0.119	0.707	1.966	2.907	24.43	1.44
3E	Ad-182c	8.19	3.59	0.122	0.639	1.737	2.584	21.18	1.30
3H	Ad-161c	9.42	3.23	0.102	0.486	1.319	1.891	18.54	1.22
3J	Cn-140c	6.85	3.96	0.169	0.936	2.498	3.456	20.45	1.50
5O	Bg-111-c	8.75	3.58	0.092	0.656	2.524	2.891	31.42	1.62
5R	Bk-100c	6.59	4.00	0.124	1.069	2.845	3.743	30.19	2.46
5S	Bg-107-c	7.64	3.69	0.113	0.895	2.186	2.875	25.44	2.47
5U	BI-93-s	8.98	3.27	0.135	0.532	1.329	1.862	13.79	1.13
6B	Fr-104-c	7.06	3.79	0.190	0.769	1.743	2.388	12.57	1.30
6F	Le-96-s	8.50	3.49	0.120	0.652	1.817	2.522	21.02	1.40
6G	Cu-75-s	6.23	4.01	0.165	0.652	1.258	3.556	21.55	0.72
6I	Bn-59-s	11.13	3.03	0.061	0.276	1.269	1.946	31.90	0.64
6K	Bn-156-c	7.38	3.54	0.198	0.901	1.928	2.603	13.15	1.58
6L	Le-160-c	6.15	4.06	0.218	1.236	2.819	3.630	16.65	1.93
6M	Cl-56-s	8.89	3.36	0.082	0.479	1.596	2.375	28.96	1.18

6.2.3 Multiple Regression Analysis

A multiple regression analysis was carried out for a better prediction of the dependent variables. The dependent variable was AASHTO T-84 and the independent variables were IT-144, FM, SSA, D_{10}, D_{30}, D_{50}, D_{60}, C_u, and C_c which are presented in Table 6.6. The variables IT-144 value, FM, D_{30}, D_{60}, and C_c were used for the analysis for AASHTO T-84 $G_{sb,Dry}$ prediction, whereas, variables IT-144 values, D_{50}, D_{60}, C_u, and C_c developed a better prediction model for AASHTO T-84 Absorption.

Various models with different combinations were run to obtain an optimum model with the best R^2 value and a normally distributed plot of residuals. The scatter plot of AASHTO T-84 $G_{sb,Dry}$ data and all the variables is presented in Figure 6.15 below. The combinations of independent variables were chosen for trial by examining if the data correlated with the dependent variable (Figures 6.15 and 6.17).

For this study, multiple regression analyses were performed for the Bulk Specific Gravity and Absorption data, which are discussed in detail in the following sections.

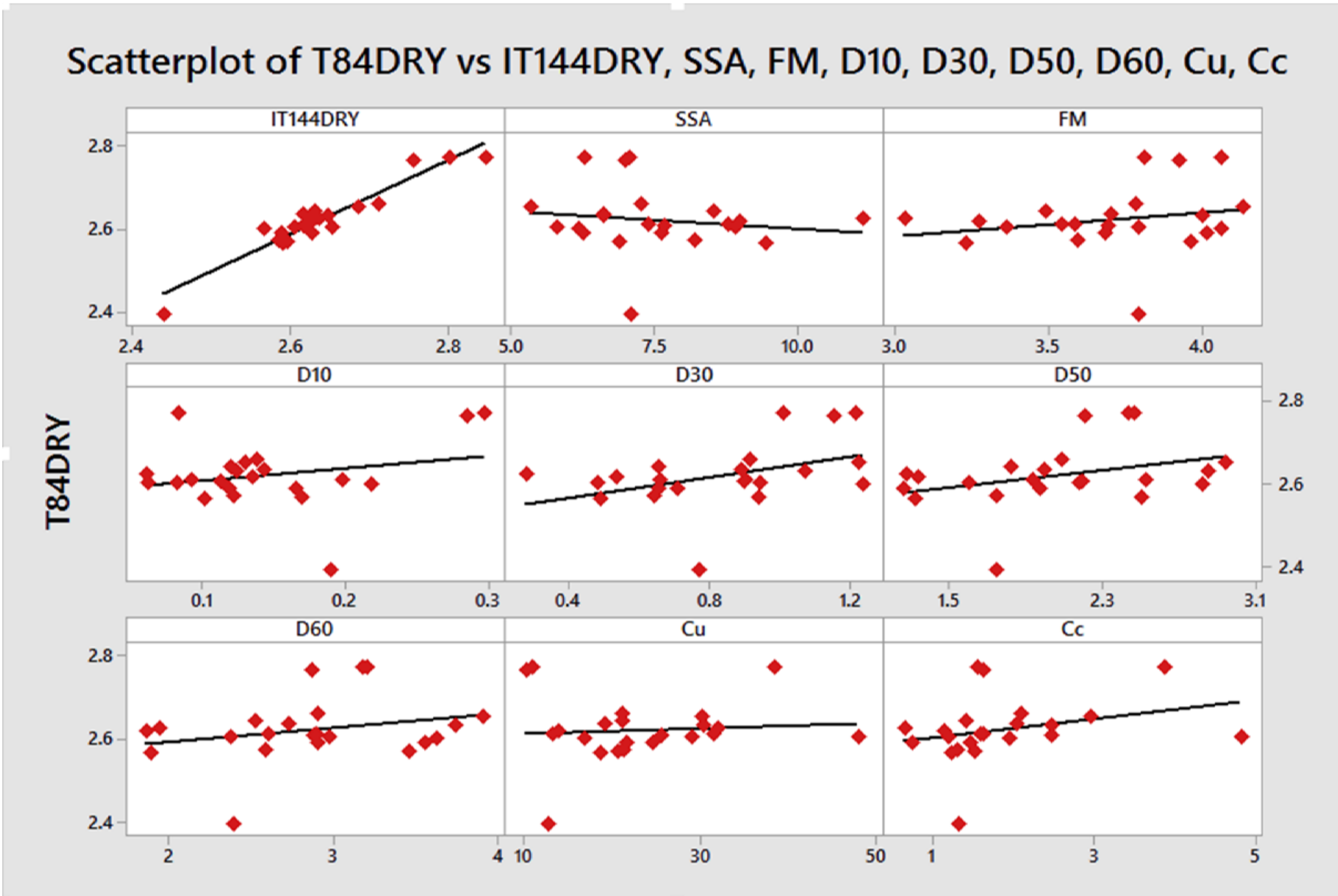


Figure 6.15 Scatter plot between AASHTO T-84 $G_{sb,Dry}$ and variables for study

Table 6.7 Coefficient estimates for the model

Coefficients	Estimate	Std.Error	t-value	Pr(>|t|)
b0	0.4884934	0.1457198	3.352	0.00405
b1	0.719851	0.0517751	13.903	2.37E-10
b2	-0.0011443	0.0003429	-3.337	0.00418
b3	0.1214714	0.0433854	2.8	0.01285
b4	0.0544418	0.0219937	2.475	0.02488
b5	-0.0106557	0.0050499	-2.11	0.050

6.2.3.1 Bulk Specific Gravity (Dry) Results

A non-linear model was developed with $G_{sb,Dry}$ value from AASHTO T-84 as the dependent variable and $G_{sb,Dry}$ from IT-144, FM, D_{30}, D_{60}, and C_c as the independent variables. The non-linear model is presented in Equation 6.3, and coefficient estimates for the model are presented in Table 6.7. The standard error column in Table 6.7 is the measure of variation of coefficient estimates from the actual average value of the independent variable. Also, the t-value is a measure of how many standard deviations the coefficient estimates from the mean (= 0) in the normal distribution plot.

$$T84G_{sb,Dry} = b_0 + b_1 \times IT144G_{sb,Dry}{}^{1.1} + b_2 \times FM^{3.9} + b_3 \times D_{30} + b_4 \times D_{60} + b_5 \times C_c{}^{1.1} \tag{6.3}$$

The p-values of less than $\alpha = 0.05$ shows that all coefficients are statistically significant in the model. The coefficient for IT-144 $G_{sb,Dry}$ has the lowest p-value and the highest estimate showing greater effect on the model. The estimate for D_{30} is lower than the IT-144 values, and the lowest estimate is of FM showing least effect among the variables considered for the model development.

Figure 6.16 shows that normal probability plot for this model is good as the residuals are very close to the line of equality. The histogram of residuals was plotted to assess the quality of the regression analysis. A scatter plot with measured values of $G_{sb,Dry}$ from AASHTO T-84 on the x-axis against values from the regression model (predicted value) is presented in Figure 6.17. An R^2 value of 94.6 percent was obtained showing that the measured and predicted values are well correlated. This shows that the model developed is good.

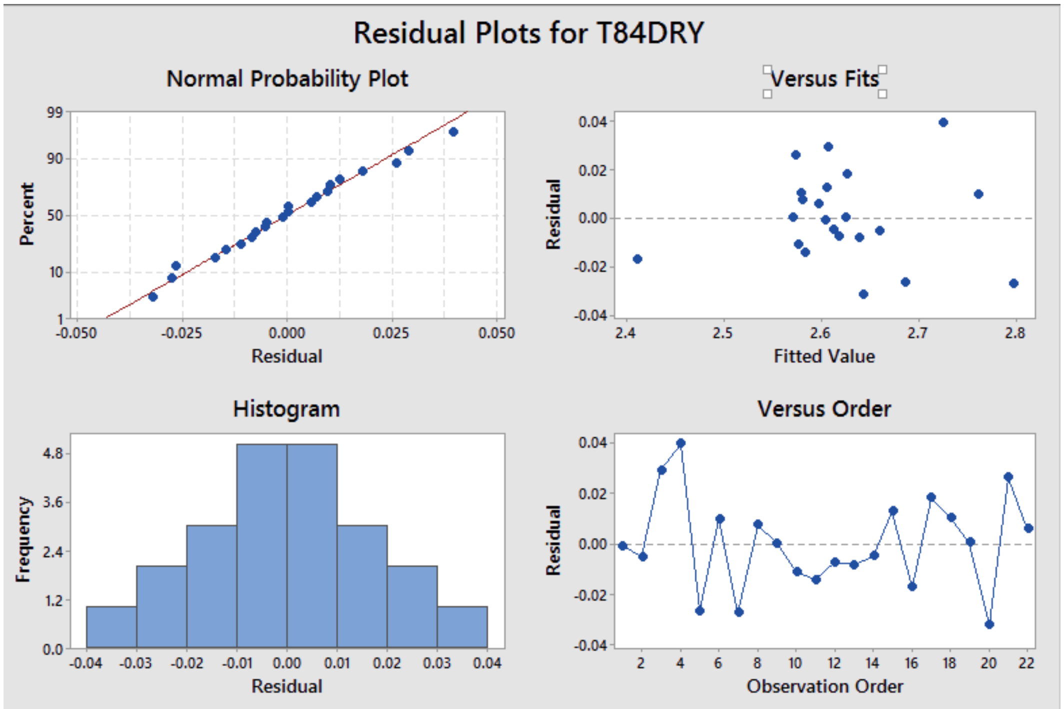


Figure 6.16 Residual plot for non-linear model for $G_{sb,Dry}$ data

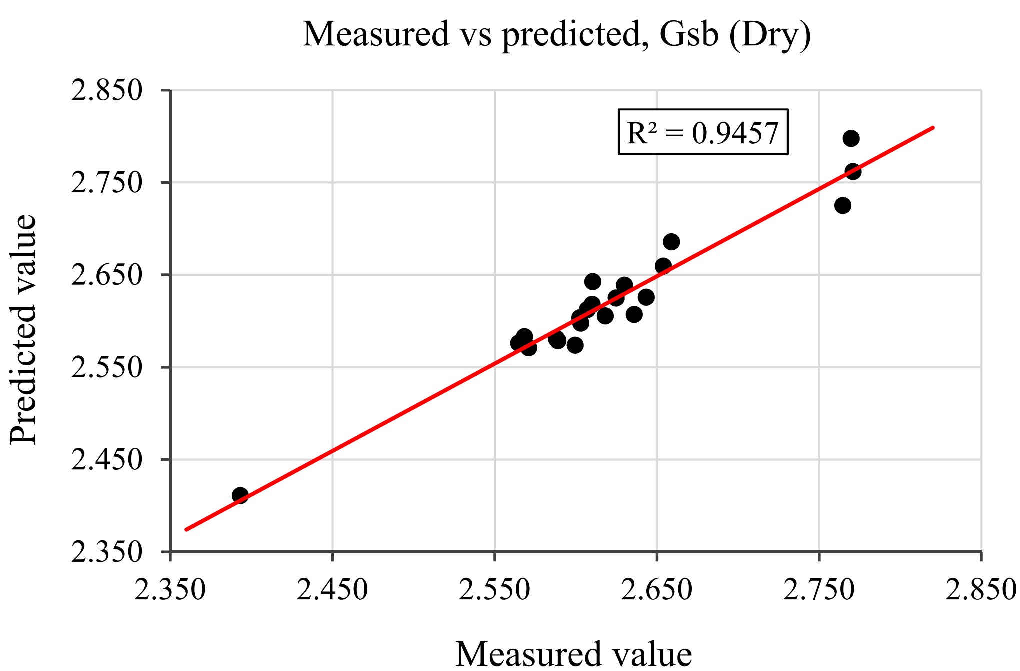


Figure 6.17 Measured vs predicted plot for non-linear model for $G_{sb,Dry}$ data

The model with the coefficient estimates is shown in the Equation 6.4 below.

$$T84G_{sb,Dry} = 0.4884934 + 0.719851 \times IT144G_{sb,Dry}{}^{1.1} - 0.0011443 \times FM^{3.9} + 0.1214714 \times D_{30} + 0.0544418 \times D_{60} - 0.0106557 \times C_c{}^{1.1} \quad (6.4)$$

6.2.3.1.1 Limitations of the Model

The range for independent variables used to develop the model are presented in Table 6.8 below. The data within the limit specified in Table 6.8 will better predict the AASHTO T-84 $G_{sb,Dry}$ values.

Table 6.8 Range of variables used to develop the model

Variables	Minimum	Maximum
$IT144G_{sb,Dry}$	2.440	2.846
FM	3.03	4.13
D_{30}	0.276	1.236
D_{60}	1.862	3.911
C_c	0.642	4.805

6.2.3.2 Absorption Results

A scatter plot between AASHTO T-84 Absorption values and the independent variables considered for the study is presented in Figure 6.18. When compared with the AASHTO T-84 data, R^2 values of around 20 percent were observed for SSA, FM, D_{10}, and D_{30} and an R^2 of less than six percent was observed for D_{50}, D_{60}, C_u, and C_c. These R^2 values are on the low side.

A non-linear model was developed with the Absorption value from AASHTO T-84 as the dependent variable and Absorption from IT-144, FM, D_{50}, and C_c as the independent variables. The non-linear model is presented in Equation 6.4. The coefficient estimates for the model are presented in the Table 6.9.

$$T84ABS = b_0 + b_1 \times IT144ABS^{2.6} + b_2 \times FM^{2.3} + b_3 \times {D_{50}}^{2.5} + b_4 \times C_c \quad (6.4)$$

Table 6.9 Coefficient estimates for the model

Coefficients	Estimate	Std.Error	t-value	Pr(>|t|)
b0	-0.42777	0.53732	-0.796	0.4376
b1	0.17219	0.02289	7.524	1.22E-06
b2	0.0712	0.03339	2.132	0.0488
b3	-0.06769	0.0306	-2.212	0.0419
b4	0.19709	0.08786	2.243	0.0394

The p-values of less than $\alpha = 0.05$ show that all the coefficients are statistically significant in the model. The coefficient for IT-144ABS has the lowest p-value, showing greater effect on the model. The estimate for C_c is the highest and estimate for D_{50} is the lowest.

The normal probability plot, shown in Figure 6.19, for the model above is good, as the residuals are very close to the line of equality. The histogram of residuals was plotted to assess the quality of the regression analysis. A scatter plot with measured values of Absorption from AASHTO T-84 in x-axis was plotted against that from regression model (predicted value) is presented in Figure 6.20. An R^2 value of 85.77 percent was obtained showing that the measured and predicted values are highly correlated. This shows that the model developed is good.

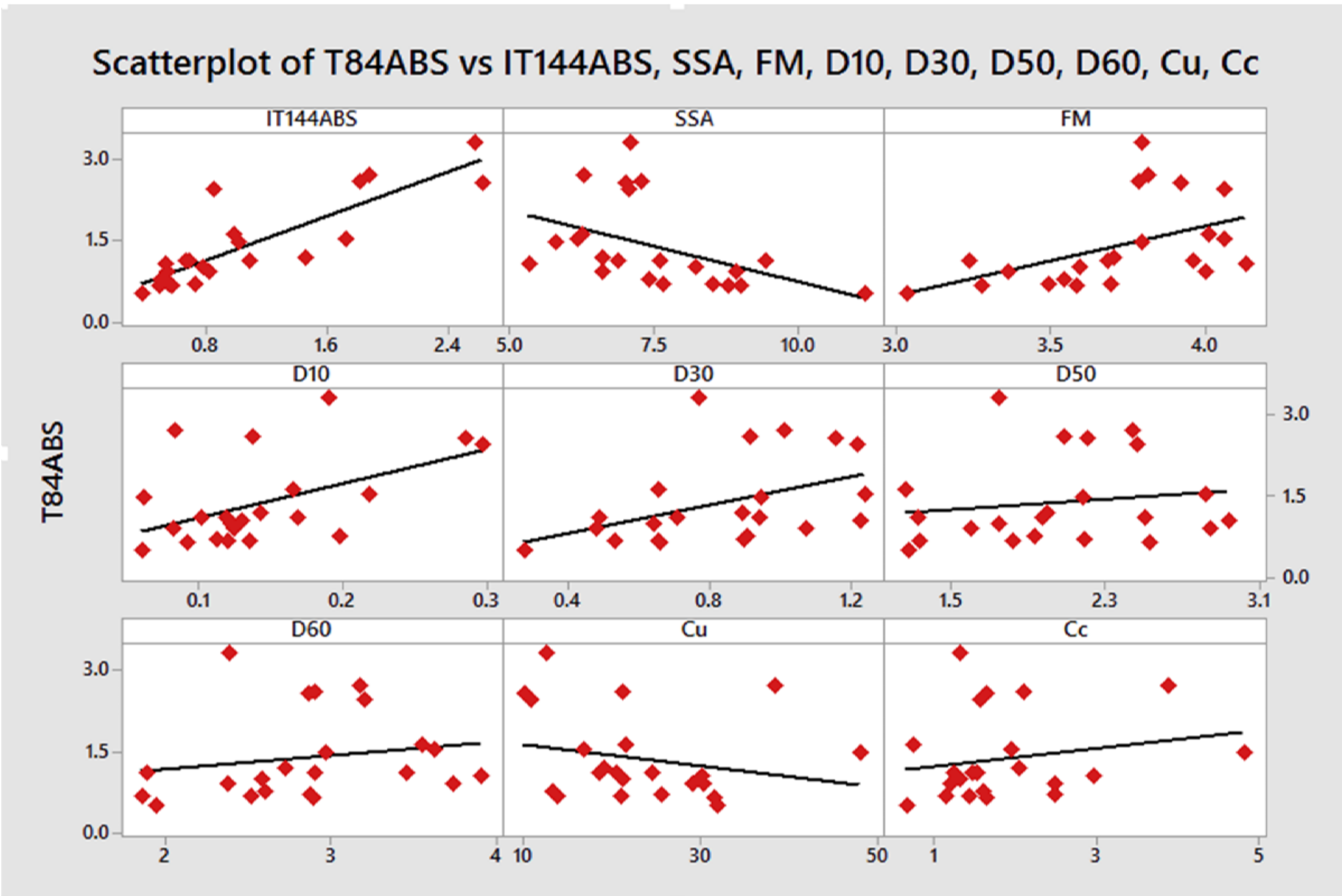


Figure 6.18 Scatter plot between AASHTO T-84 Absorption and variables for study

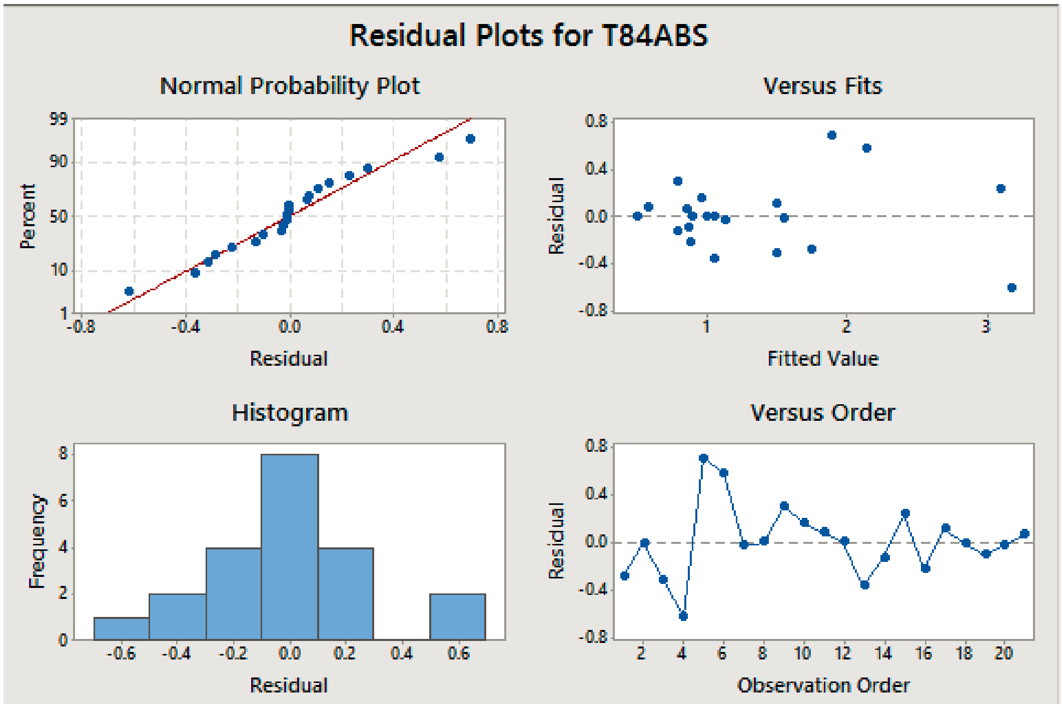


Figure 6.19 Scatter plot for non-linear model for Absorption data

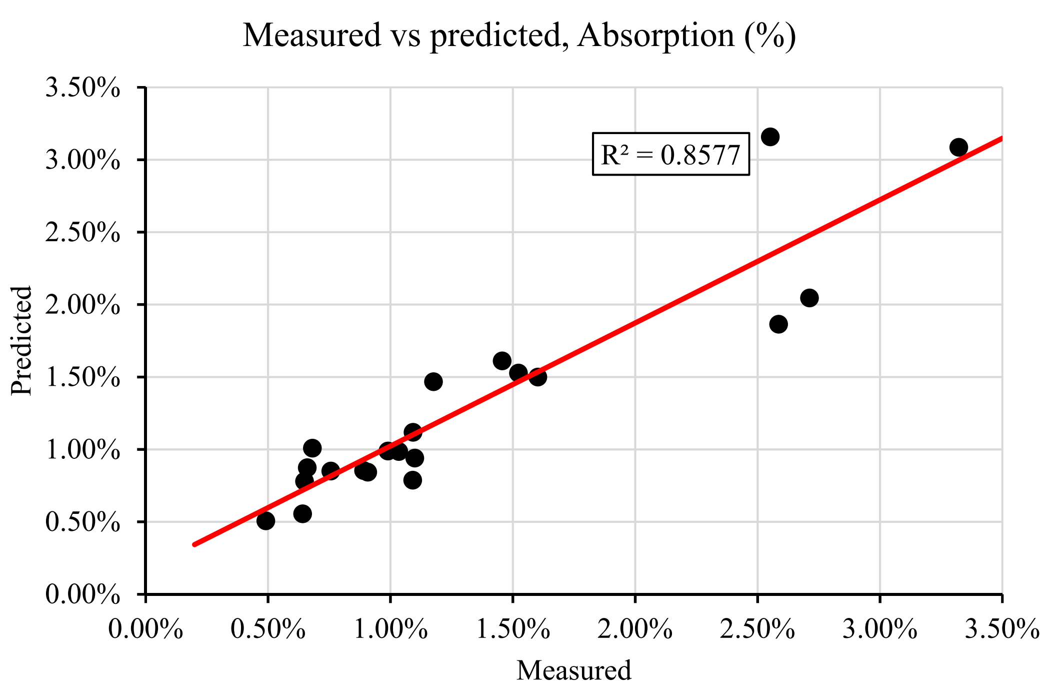


Figure 6.20 Measured vs predicted plot for non-linear model for Absorption (%) data

The model with the coefficient estimates is shown in the Equation 6.5 below.

$$T84ABS = -0.42777 + 0.17219 \times IT144ABS^{2.6} + 0.0712 \times FM^{2.3} - 0.06769 \times {D_{50}}^{2.5} + 0.19709 \times C_c \quad (6.5)$$

6.2.3.2.1 Limitations of the Model

The range for independent variables used to develop the model are presented in Table 6.10 below. The data within the limit specified in Table 6.10 will better predict the AASHTO T-84 Absorption values.

Table 6.10 Range of variables used to develop the model

Variables	Minimum	Maximum
IT144ABS	0.38	2.63
FM	3.03	4.13
D_{30}	0.276	1.236
D_{60}	1.862	3.911
C_c	0.642	4.805

6.3 Model Validation

The models developed in the previous sections were validated using a different set of data. For this study, the models were developed using the UI test results.

ALLWEST performed tests on 20 aggregate and the data from two test methods are presented in Table 6.11. These data will be used for the model validation. Figures 6.21, 6.22, 6.23, and 6.24 show the difference and comparison of $G_{sb,Dry}$ and Absorption results of the tests performed at UI and AW. In most of the cases, AW values were higher for $G_{sb,Dry}$ than the UI for AASHTO T-84 test method where the values ranged from 0 to 0.027. Whereas, for IT-144 method, UI values were higher for $G_{sb,Dry}$ than the AW in most of the cases where the values ranged from 0.001 to 0.075. For Absorption values, the difference between AW and UI ranged from 0 to 0.30 percent for AASHTO T-84 method whereas, for IT-144 method the difference ranged from 0.01 to 0.90 percent.

The test results from ALLWEST (AW) will be used for the model validation, which is discussed in this section. For the simple linear regression model, IT144$G_{sb,Dry}$ and IT144ABS values from AW were used as the independent variable to predict the AW AASHTO T-84 values. Figures 6.25 and 6.26 show the scatter plot between the measured and predicted AW values for $G_{sb,Dry}$ and Absorption. The acceptable models are as follows.

Linear regression model

$$T84ABS = 0.1819 + 1.074 \times IT144ABS$$

$$T84G_{sb,Dry} = 0.2518 + 0.8981 \times IT144G_{sb,Dry}$$

Multiple regression model

$$T84G_{sb,Dry} = 0.4884934 + 0.719851 \times IT144{G_{sb,Dry}}^{1.1} - 0.0011443 \times FM^{3.9} + 0.1214714 \times D_{30} + 0.0544418 \times D_{60} - 0.0106557 \times {C_c}^{1.1}$$

$$T84ABS = -0.42777 + 0.17219 \times IT144ABS^{2.6} + 0.0712 \times FM^{2.3} - 0.06769 \times {D_{50}}^{2.5} + 0.19709 \times C_c$$

Table 6.11 ALLWEST test results for model validation

UI-ID	ITD-ID	T-84				IT-144			
		DRY	SSD	App.	Abs.	DRY	SSD	App.	Abs.
1D	Kt-213-c	2.623	2.658	2.719	1.36%	2.648	2.674	2.721	1.02%
1N	Kt-222-c	2.635	2.668	2.725	1.26%	2.677	2.691	2.715	0.52%
1P	Kt-215-c	2.634	2.663	2.712	1.09%	2.617	2.660	2.737	1.67%
2C	WCW-23-c								
2Q	Id 256-c	2.644	2.717	2.852	2.76%	2.578	2.668	2.833	3.48%
2T	WCW-18-c	2.735	2.815	2.974	2.94%	2.825	2.866	2.945	1.45%
2V	Np-82-c	2.770	2.830	2.949	2.20%	2.801	2.843	2.923	1.49%
3A	Ad-136	2.591	2.615	2.653	0.90%	2.581	2.609	2.657	1.10%
3E	Ad-182-c	2.563	2.587	2.627	0.95%	2.587	2.606	2.636	0.73%
3H	Ad-161-c	2.568	2.596	2.641	1.08%	2.597	2.613	2.639	0.61%
3J	Cn-140-c	2.559	2.592	2.647	1.30%	2.564	2.590	2.632	1.01%
5O	Bg-111-c	2.601	2.618	2.645	0.64%	2.610	2.624	2.648	0.55%
5R	Bk-100-c	2.629	2.646	2.673	0.62%	2.655	2.665	2.682	0.38%
5S	Bg-107-c	2.591	2.613	2.648	0.83%	2.615	2.628	2.648	0.48%
5U	BI-93-s	2.606	2.624	2.654	0.70%	2.616	2.629	2.650	0.49%
6B	Fr-104-c								
6F	Le-96-s	2.618	2.643	2.685	0.95%	2.650	2.661	2.681	0.44%
6G	Cu-75-s	2.604	2.638	2.695	1.30%	2.657	2.669	2.688	0.44%
6I	Bn-59-s	2.622	2.636	2.658	0.52%	2.630	2.636	2.646	0.23%
6K	Bn-156-c	2.594	2.618	2.657	0.92%	2.638	2.646	2.659	0.30%
6L	Le-160-c	2.585	2.626	2.695	1.58%	2.523	2.582	2.681	2.34%
6M	Cl-56-s	2.585	2.615	2.664	1.14%	2.590	2.619	2.666	1.11%

Note: AW did not test Samples 2C and 6B

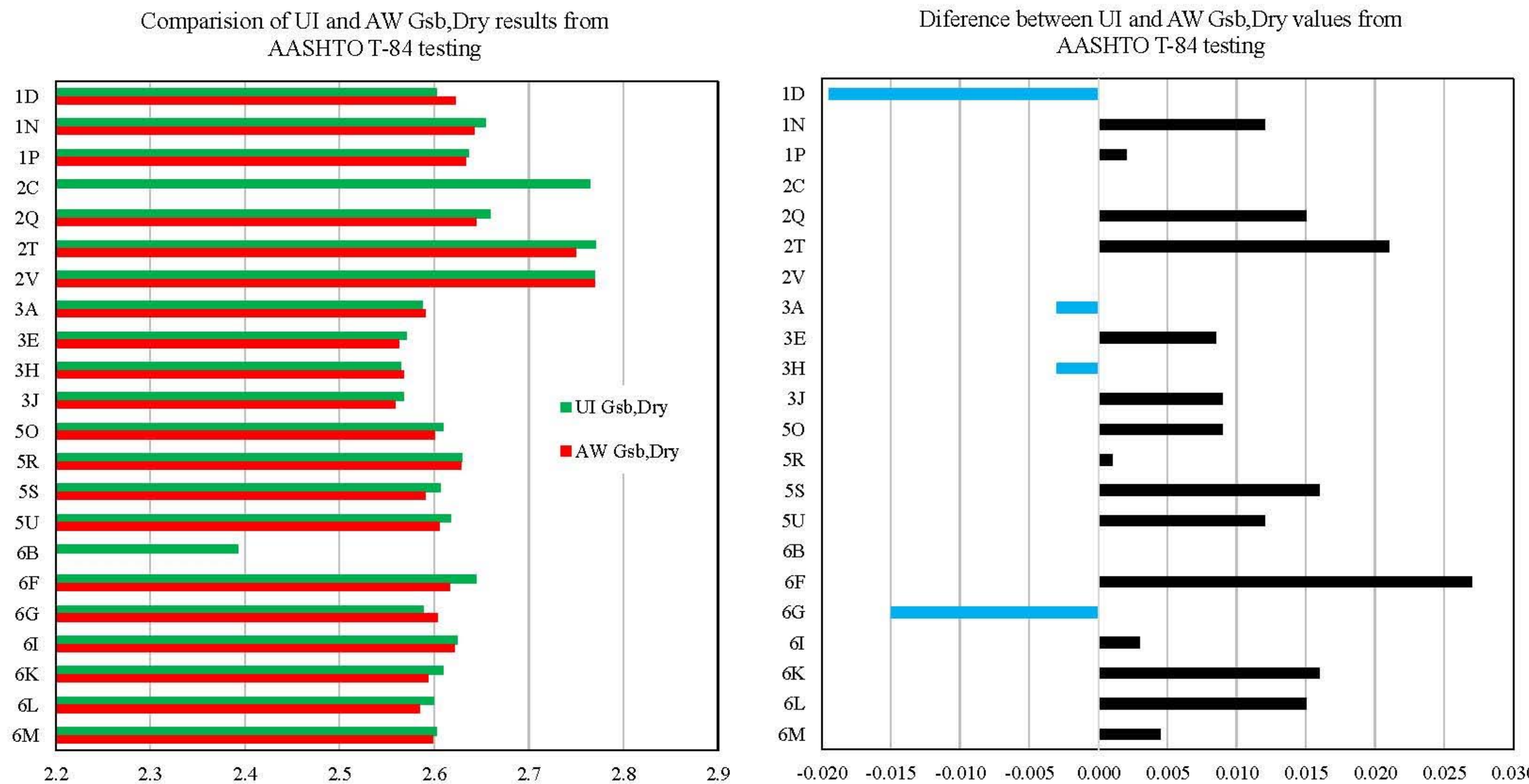
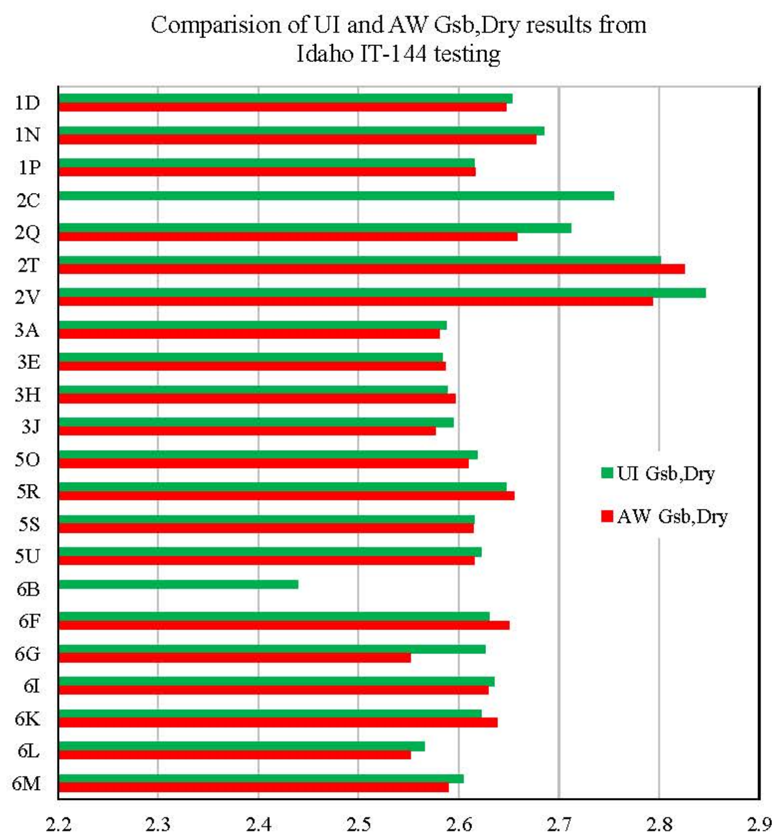


Figure 6.21 Comparison of AASHTO T-84 $G_{sb,Dry}$ results between UI and AW



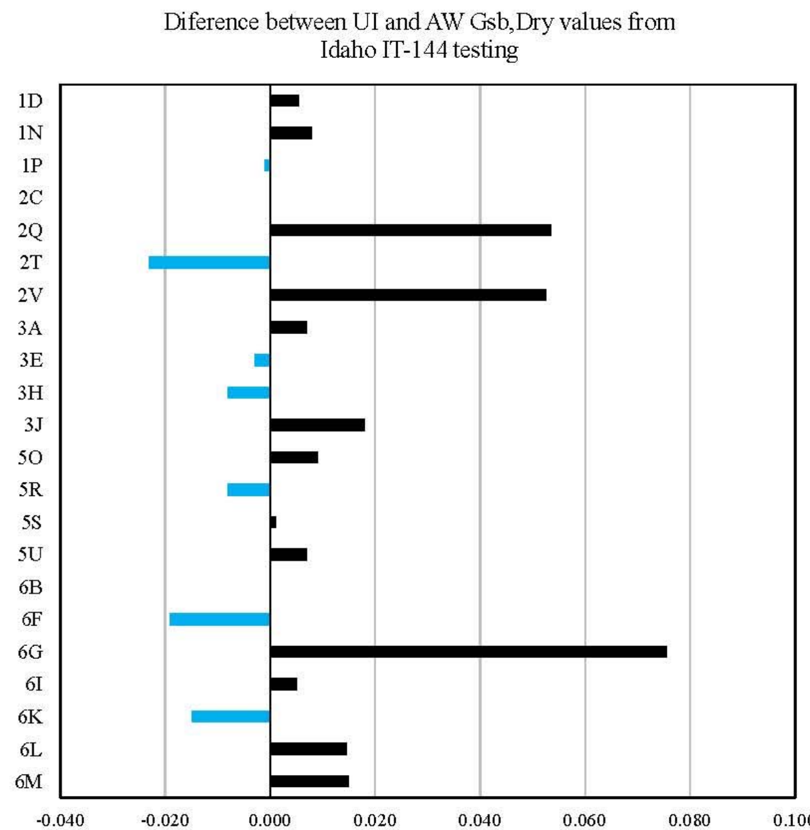
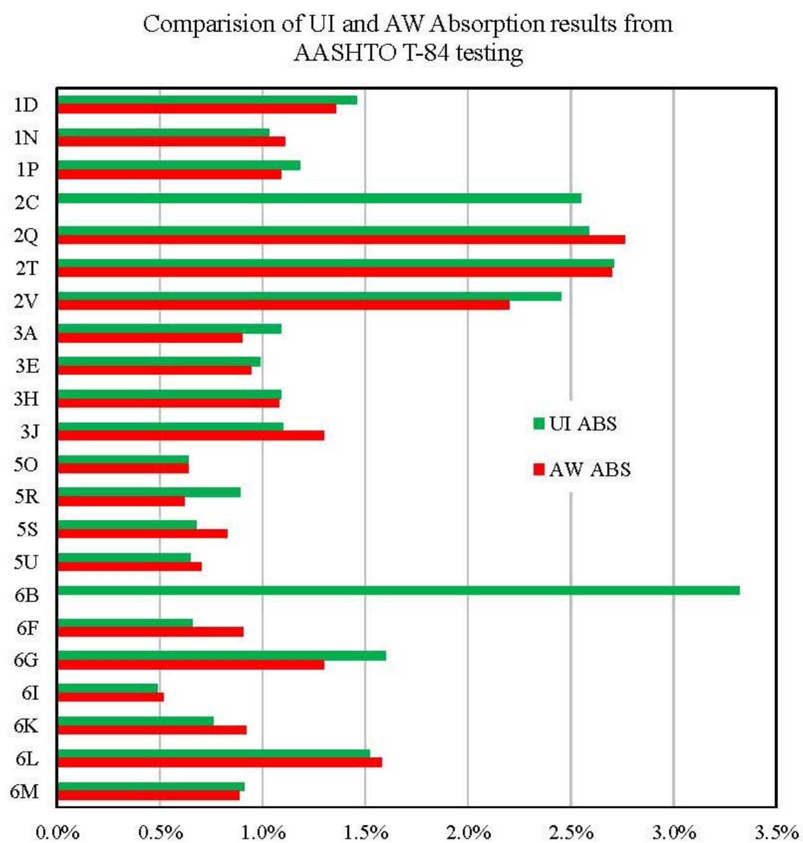


Figure 6.22 Comparison of IT-144 $G_{sb,Dry}$ results between UI and AW



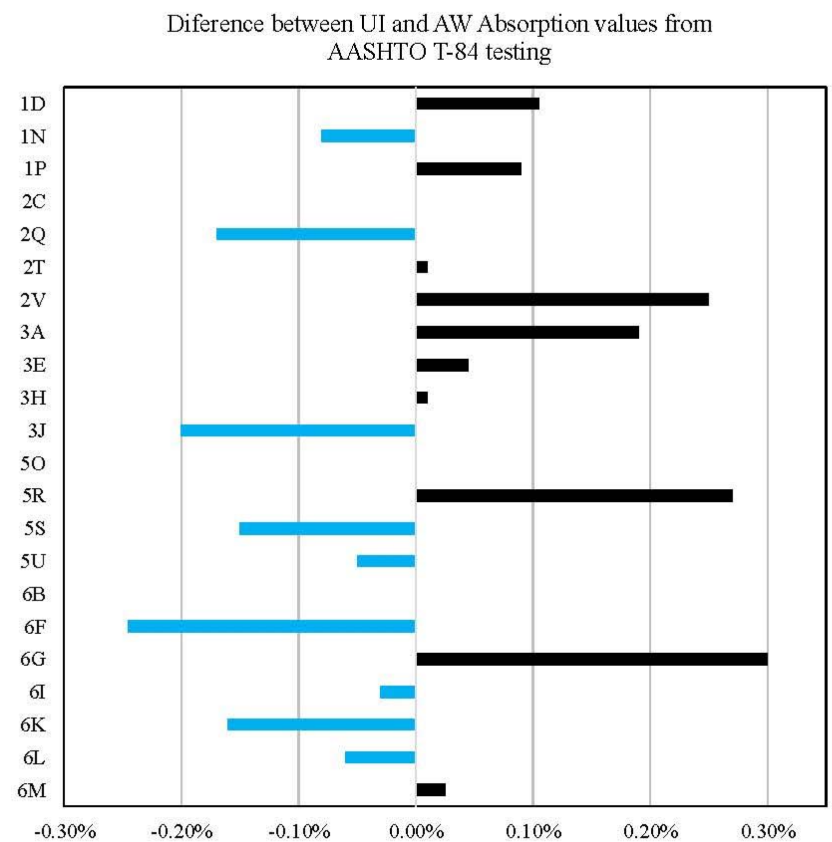


Figure 6.23 Comparison of AASHTO T-84 Absorption results between UI and AW

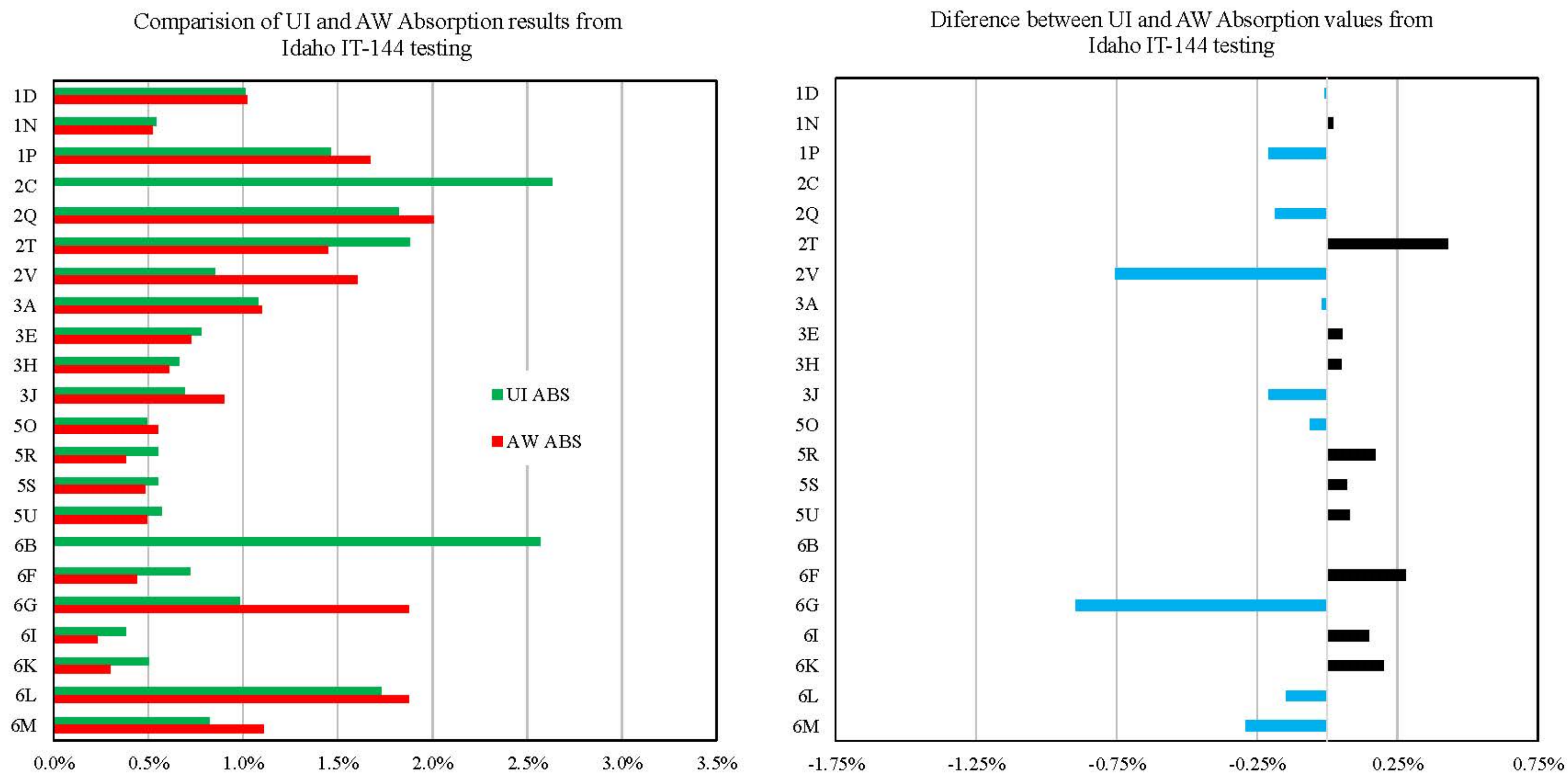


Figure 6.24 Comparison of IT-144 Absorption results between UI and AW

Figures 6.25, 6.26 show the scatter plot of measured $G_{sb,Dry}$ values versus predicted values for the AW results for the simple and multiple regression analyses. Similarly, Figures 6.27 and 6.28 show the scatter plot of measured values of absorption against predicted values for AW results for the simple and multiple regression analysis. Measured values are the $G_{sb,Dry}$ and Absorption values obtained from IT-144 tests and these values are used to predict the AASHTO T-84 $G_{sb,Dry}$ and Absorption values for AW. Measured values are in x-axis and predicted values are in y–axis.

Table 6.12 summarizes the R^2 obtained for the AW data using the model based on using UI results. An R^2 of 92.30 and 74.89 percent was obtained using the simple regression analysis and multiple regression analysis for $G_{sb,Dry}$ respectively which shows a very good correlation. A higher R^2 of 53.20 percent was obtained while using the multiple regression analysis for Absorption which is a good correlation.

Table 6.12 R^2 values for model validation

Model	$G_{sb,Dry}$		Absorption	
	Model Development	Model Validation	Model Development	Model Validation
Simple Regression Analysis	90.53%	**92.30%**	84.60%	50.39%
Multiple Regression Analysis	94.57%	74.89%	85.77%	**53.20%**

A better R^2 value was obtained using simple regression analysis for the $G_{sb,Dry}$ values than using the multiple regression analysis during data validation. Therefore, it is recommended that simple regression model be used to predict the AASHTO T-84 $G_{sb,Dry}$ results using the IT-144 $G_{sb,Dry}$ test results.

A better R^2 value was obtained using multiple regression analysis for the Absorption values than using the simple regression analysis during data validation. Therefore, it is recommended that multiple regression model be used to predict the AASHTO T-84 Absorption results using the IT-144 Absorption test results.

On the basis of the above results, the best statistical models are:

Model for $G_{sb,Dry}$:

$$T84G_{sb,Dry} = 0.2518 + 0.8981 \times IT144G_{sb,Dry} \qquad (6.6)$$

Model for Absorption:

$$T84ABS = -0.42777 + 0.17219 \times IT144ABS^{2.6} + 0.0712 \times FM^{2.3} - 0.06769 \times {D_{50}}^{2.5} + 0.19709 \times C_c \qquad (6.7)$$

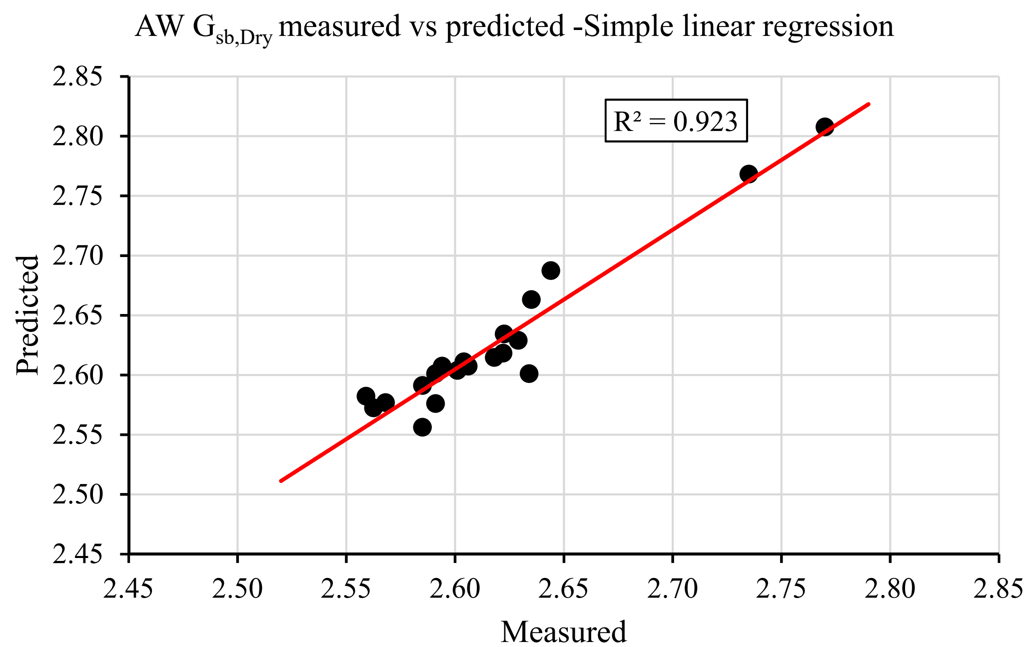


Figure 6.25 Measured vs predicted values of $G_{sb,Dry}$ for AW results for simple linear regression

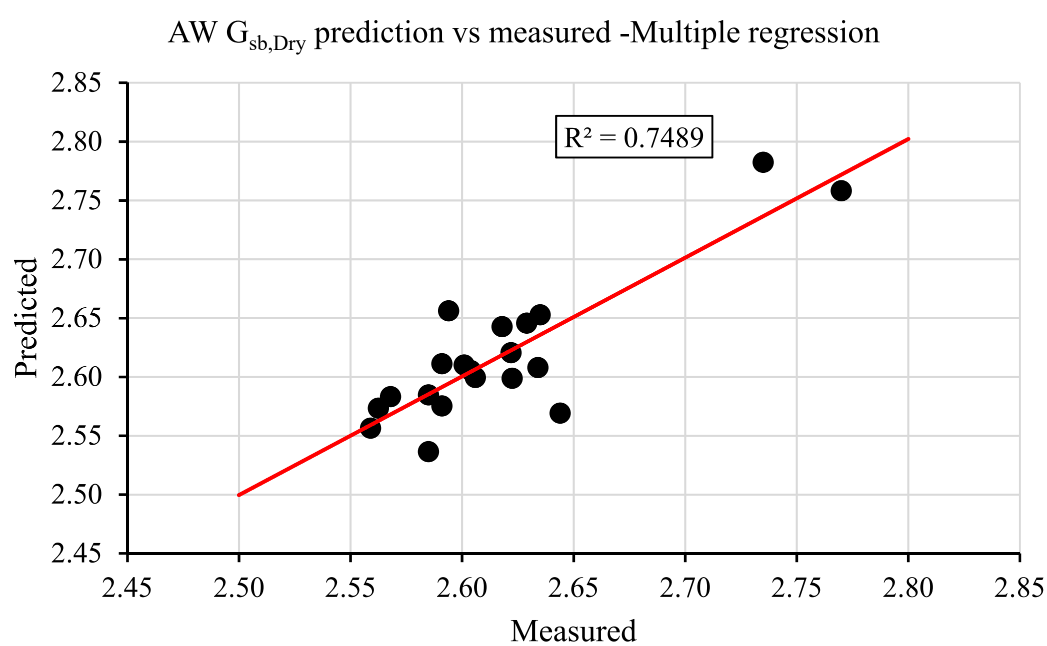


Figure 6.26 Measured vs predicted values of $G_{sb,Dry}$ for AW results for multiple regression

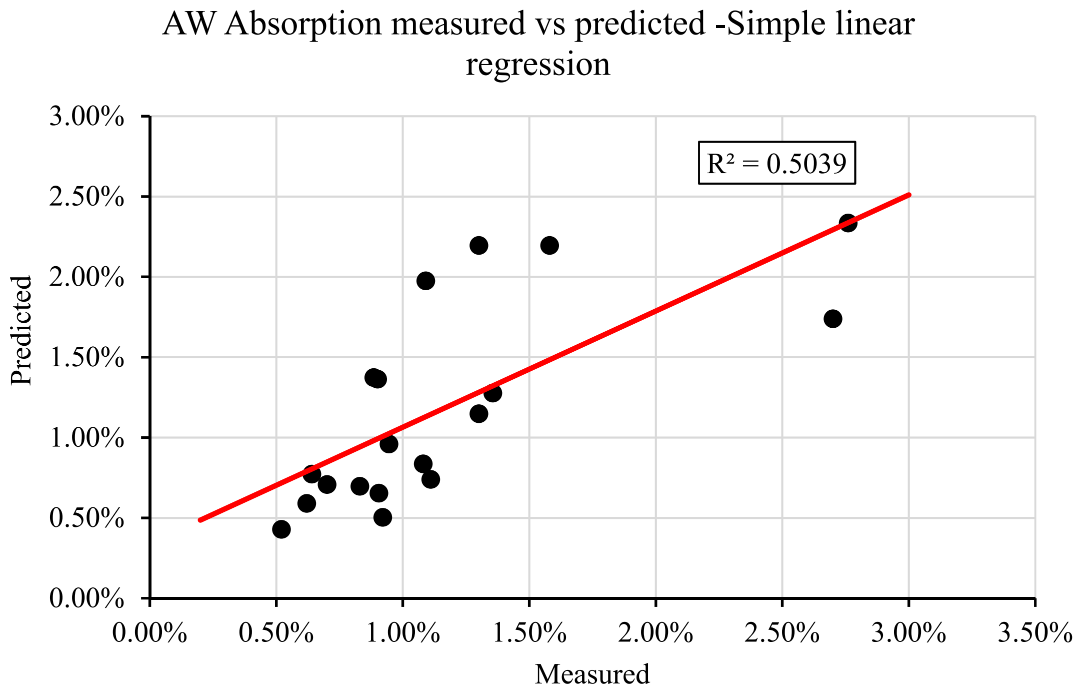


Figure 6.27 Measured vs predicted values of Absorption for AW for simple linear regression

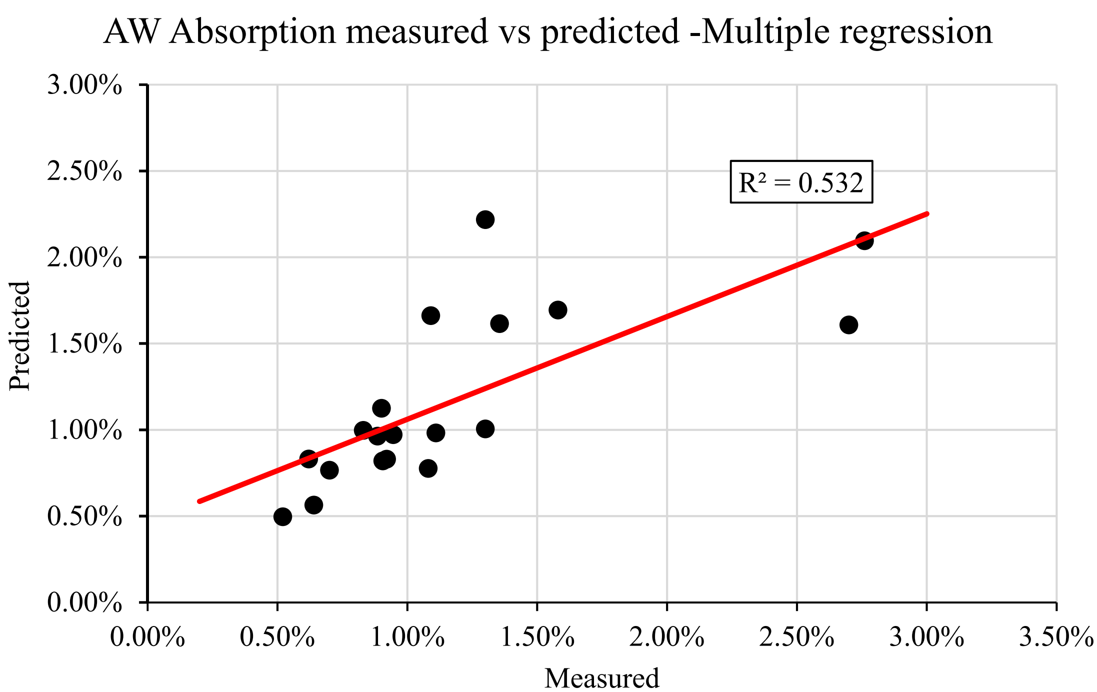


Figure 6.28 Measured vs predicted values of Absorption for AW results for multiple regression

CHAPTER 7 SUMMARY, CONCLUSIONS AND RECOMMENDATION

7.1 Summary

The AASHTO T-84 method is a traditional test method which takes almost 3 days to complete and it also introduces operator dependent errors in the results. Whereas, the IT-144 test method is gaining popularity because of its efficiency, less testing time, and less variabilities in the test procedures. Many DOTs including ITD want to use the simpler and easier test method – IT-144 as a practical testing method.

This study was conducted to develop models which could correlate the IT-144 test results with AASHTO T-84 test results. For this purpose, the typical aggregate samples collected from the popular quarry sites used by the ITD were tested using AASHTO T-84 and Idaho IT-144 test methods. Models were developed to predict the AASHTO T-84 values using the IT-144 values.

Additional tests were performed to check the effect of variabilities on the test methods. A round robin experiment was performed involving ITD (Boise), and material testing consultants: ALLWEST (AW) and STRATA to confirm that the results were comparable between the participants.

The values of aggregate properties like Specific Gravities (SGs) and absorption obtained from the test methods were analyzed using statistical software (SPSS, Minitab, R, and Microsoft Excel). Simple regression analysis and multiple regression analyses were performed to develop linear and non-linear prediction models. AASHTO T-84 results were used as the dependent variable and IT-144 test results, and other variables like particle sizes, Specific Surface Area (SSA) of the aggregates, Fineness Modulus (FM) of the aggregates, Coefficient of Curvature (C_c), and Coefficient of Uniformity (C_u) were used as the predictor variables. Finally, AASHTO T-84 values were predicted using IT-144 results.

7.2 Conclusions

The data from UI were used to develop the regression models. The ALLWEST results were used to validate the proposed models. Based on the results of the study, the following conclusions may be made:

1. The paired t-test indicated a statistically significant difference in the mean values of all specific gravities and Absorption between AASHTO T-84 and the IT-144 test methods.

2. In most of the cases, IT-144 over estimated the values of $G_{sb,Dry}$ compared to the AASHTO T-84.

3. A linear regression model was developed using the $G_{sb,Dry}$, $G_{sb,SSD}$, G_{sa}, and Absorption values from AASHTO T-84 as the dependent variable and $G_{sb,Dry}$, $G_{sb,SSD}$, G_{sa}, and Absorption from IT-144 as the independent variable. The analysis generated the following model with R^2 as presented in the table.

Models	R^2 (%)	Eq.
$T84G_{sb,Dry} = 0.2518 + 0.8981 \times IT144G_{sb,Dry}$	90.53	(7.1)
$T84G_{sb,SSD} = 0.0702 + 0.9704 \times IT144G_{sb,SSD}$	96.50	(7.2)
$T84APP = -0.2203 + 1.084 \times IT144APP$	98.20	(7.3)
$T84ABS = 0.1819 + 1.074 \times IT144ABS$	84.55	(7.4)

4. Several groupings of material types were analyzed for possible significant influence, but the correlation was very poor.

5. A non-linear model was developed with $G_{sb,Dry}$ value from AASHTO T-84 as the dependent variable and $G_{sb,Dry}$ from IT-144, FM, D_{30}, D_{60}, and C_c as the independent variables. The analysis generated the following model. An R^2 value of 94.6 percent was obtained showing the measured and predicted values are well correlated.

$$T84G_{sb,Dry} = 0.4884934 + 0.719851 \times IT144{G_{sb,Dry}}^{1.1} - 0.0011443 \times FM^{3.9} + 0.1214714 \times D_{30} + 0.0544418 \times D_{60} - 0.0106557 \times {C_c}^{1.1} \quad (7.5)$$

6. A non-linear model was developed with Absorption value from AASHTO T-84 as the dependent variable and Absorption from IT-144, FM, SSA, D50, and Cc as the independent variables. An R^2 value of 85.77 percent was obtained showing the measured and predicted values are highly correlated.

$$T84ABS = -0.42777 + 0.17219 \times IT144ABS^{2.6} + 0.0712 \times FM^{2.3} - 0.06769 \times {D_{50}}^{2.5} + 0.19709 \times C_c \quad (7.6)$$

7. The models developed using UI data were validated using the AW data. Data validation was better for simple linear regression for $G_{sb,Dry}$ and multiple regression for Absorption.

7.3 Recommendations

Based on the results of this study,

1. It is recommended that the Idaho IT-144 test method be adopted as it is faster, easier, repeatable, and produces results which are close to the AASHTO T-84 method.

2. The following models are recommended for estimating AASHTO T-84 values using results from the IT-144 method:

Bulk Dry Specific Gravity:

$$T84G_{sb,Dry} = 0.2518 + 0.8981 \times IT144G_{sb,Dry} \quad (7.7)$$

Absorption:

$$T84ABS = -0.42777 + 0.17219 \times IT144ABS^{2.6} + 0.0712 \times \mathrm{FM}^{2.3} - 0.06769 \times {D_{50}}^{2.5} + 0.19709 \times C_c \quad (7.8)$$

3. Further refinements to these models should be considered following observations of field performance of the HMA.

4. It is recommended that additional aggregates be tested to increase the sample size which may allow for the development of prediction models which consider the material types.

REFERENCES

[1] G. Sholar, G. Page, J. Musselman, P. Upshaw, and H. Moseley, “Investigation of the CoreLok for Maximum, Aggregate, and Bulk Specific Gravity Tests,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1907, pp. 135–144, 2005.

[2] D. Richardson and L. Steven, “Calibration of The CoreLok Method for Determination of Missouri Aggregate Specific Gravities,” no. June, 2005.

[3] B. D. Browell and N. V Baker, “Evaluation of New Test Procedures for Determining the Bulk Specific Gravity of Fine Aggregate,” 2005.

[4] L. A. Cooley, D. Ph, and K. Williams, “Aggregate Absorption in HMA Mixtures,” 2013.

[5] R. West, , Dukatz, E., Haddock, J., Hall, K., Kliever, J., Marek, C., Musselman, J., and Regimand, A., “A review of aggregate and asphalt mixture specific gravity measurements and their impacts on asphalt mix design properties and mix acceptance,” *Techbr. FHWA-HIF-11-033, US Dept. Transp. Fed. Highw. Adm. Off. Pavement Technol.*, no. December, 2010.

[6] ITD, “Specific Gravity and Absorption of Fine Aggregate Using Automatic Vacuum Sealing (CoreLok) Method,” 2008.

[7] A. G. Allan Alderson, “AP-T55/06 CoreLok Evaluation,” 2006.

[8] A. Rajagopal and D. Crago, “A comparative Evaluation of the Corelok Device in Determining Reliable Bulk Specific Gravity and Maximum Specific Gravity Test Results,” no. 134187, 2007.

[9] S. A. Cross, “Evaluation of Test Methods for Determination of Aggregate Specific Gravity,” no. 2169, 2005.

[10] J. Zaniewski, L. Bessette, H. Rashidi, and R. Bikya, “Evaluation of Methods for Measuring Aggregate Specific Gravity,” 2012.

[11] K. Hall, “Using a Single Test to Determine Specific Gravity and Absorption of Aggregate Blends,” *Transp. Res. Rec.*, vol. 1874, no. 1, pp. 3–10, 2004.

[12] P. Khandal, R. Mallick, and M. Huner, “Measuring Bulk Specific Gravity of fine Aggregates.pdf,” *Transp. Res. Rec. J. Transp. Board*, vol. 1721, no. 2000, pp. 81–90, 2000.

[13] AASHTO T 84-00 (2004), “Specific Gravity and Absorption of Fine Aggregate,” *AASHTO*, vol. 00, no. 2004, pp. 1–8, 2011.

[14] A. B. Cerato, “Influence of specific surface area on geotechnical characteristics of fine-grained soils,” *Unpubl. MSc Thesis*, no. May, 2001.

[15] E. L. Howard, *Proceedings of the American Concrete Institute*, Vol. 54, 1958.

[16] J. C. Pearson, *A Simple Titration Method for Determining the Absorption of Fine Aggregate*. Rock Products, Vol. 32, 1929.

[17] J. R. Martin, *Two Years of Highway Research at Oklahoma A&M. Proceedings of the Association of Asphalt Paving Technologists*, Vol. 19, 1950, pp. 41-54.

[18] E. L. Saxer, *A Direct Method of Determining Absorption and Specific Gravity of Aggregates*. Rock Products, Vol. 87, 1965, pp. 77-79.

[19] B. P. Hughes, and B. Bahramian. *An Accurate Laboratory Test for Determining the Absorption of Aggregates.* Materials Research and Standards, 1967, pp. 18-23.

[20] P. S. Khandal, and D.Y. Lee. *An Evaluation of the Bulk Specific Gravity for Granular Materials.* Highway Research Record 307, HRB, National Research Council, Washington D.C., pp. 44-55.

[21] J. S. Dana, and R. J. Peters. *Experimental Moisture Determination for Defining Saturated Surface Dry State of Highway Aggregates.* Arizona Highway Department, Report No. 6, HPR 1-11, June 1974, p. 153.

[22] P. E. Krugler, M. Tahmoressi, and D. A. Rand. *Improving the Precision of Test Methods Used in VMA Determination.* Asphalt Paving Technology, Vol. 61, 1992, pp. 272-203.

APPENDIX

Lab data

Table A.1 Raw data and results for the Idaho IT-144 Tests (Note all weights are in grams)

UI - ID	ITD - ID	Date	Average Container Calibration Weight	Average Dry Sample Weight	Average Sample Weight in Container Filled with Water	Bag Weight	Dry Sample Weight	Weight of Sealed Sample Opened in Water	Percent Absorption	Apparent Density	Bulk Specific Gravity (SSD)	Bulk Specific Gravity (BSG)
A1	Ad 136	3/9/2017	4221.1	560.5	4568.8	23.0	1224.7	762.2	1.067	2.662	2.616	2.589
A2	Ad 136	3/9/2017	4221.1	521.5	4544.6	22.9	1221.9	760.9	1.139	2.665	2.616	2.586
A3	Ad 136	3/9/2017	4221.1	533.6	4552.1	23.1	1050.3	653.1	1.045	2.661	2.616	2.589
A4	Ad 136	3/9/2017	4221.1	537.5	4554.5	22.7	1024.3	637.1	1.088	2.662	2.615	2.587
B1	Fr 104c	3/6/2017	4220.9	600.3	4583.7	22.7	1468.0	901.7	2.550	2.603	2.504	2.441
B2	Fr 104c	3/6/2017	4220.9	537.1	4545.4	22.9	1257.3	772.5	2.680	2.607	2.502	2.436
B3	Fr 104c	3/6/2017	4220.9	591.7	4578.3	23.0	1245.3	763.5	2.468	2.598	2.502	2.441
B4	Fr 104c	3/6/2017	4220.9	613.0	4591.4	23.3	1113.6	683.6	2.594	2.605	2.503	2.440
C1	WCW 23	3/7/2017	4220.8	558.3	4584.4	22.8	1197.5	792.1	2.671	2.972	2.827	2.753
C2	WCW 23	3/7/2017	4220.8	630.0	4631.2	22.9	1164.7	769.9	2.569	2.969	2.829	2.758
C3	WCW 23	3/7/2017	4220.8	674.0	4659.7	22.9	1078.0	712.5	2.646	2.969	2.826	2.753
C4	WCW 23	3/7/2017	4220.8	532.6	4567.9	22.7	1197.2	792.4	2.674	2.975	2.830	2.756
C5	WCW 23	4/12/2017	4221.0	542.9	4574.4	22.9	1138.4	751.7	2.576	2.963	2.824	2.753
D1	Kt 213	3/8/2017	4221.0	522.4	4549.8	22.9	1050.6	662.5	0.954	2.724	2.681	2.655
D2	Kt 213	3/8/2017	4221.0	550.4	4567.4	23.1	1066.3	672.7	1.016	2.726	2.680	2.653
D3	Kt 213	3/8/2017	4221.0	526.1	4552.3	23.1	1092.2	688.5	0.864	2.722	2.683	2.660
D4	Kt 213	3/8/2017	4221.0	529.0	4554.0	22.7	1064.4	671.4	0.954	2.725	2.681	2.656
D5	Kt 213	8/31/2017	4221.2	500.0	4535.6	22.8	1054.4	665.2	1.150	2.726	2.674	2.643
D6	Kt 213	9/5/2017	4221.2	500.0	4536.1	22.7	1000.0	630.9	0.979	2.727	2.682	2.656
D7	Kt 213c	2/14/2018	4220.8	500.0	4535.5	28.4	1000.0	630.7	1.160	2.730	2.677	2.647
E1	Ad 182	7/20/2017	4221.3	525.6	4546.1	22.6	1078.3	667.1	0.882	2.638	2.601	2.578
E2	Ad 182	8/30/2017	4221.0	501.2	4531.1	22.9	1127.8	697.6	0.666	2.637	2.608	2.591
E3	Ad 182	9/5/2017	4221.2	500.0	4530.4	22.7	1000.0	618.6	0.802	2.639	2.605	2.584
F1	Le -96s	11/2/2017	4221.1	500.0	4533.3	22.7	1000.0	624.2	0.703	2.678	2.647	2.629
F2	Le -96s	1/2/2018	4220.2	500.0	4533.0	23.0	1000.0	625.2	0.709	2.686	2.654	2.636
F3	Le 96s	2/13/2017	4221.1	500.0	4533.4	28.1	1000.0	623.9	0.758	2.680	2.647	2.627

Table A.1 continued (Note all weights are in grams)

UI - ID	ITD - ID	Date	Average Container Calibration Weight	Average Dry Sample Weight	Average Sample Weight in Container Filled with Water	Bag Weight	Dry Sample Weight	Weight of Sealed Sample Opened in Water	Percent Absorption	Apparent Density	Bulk Specific Gravity (SSD)	Bulk Specific Gravity (BSG)
G1	Cu-75s	10/31/2017	4220.5	500.0	4533.4	22.9	1000.0	626.8	0.964	2.697	2.654	2.629
G2	Cu -75s	1/4/2018	4220.3	500.0	4532.9	22.7	1000.0	626.5	0.999	2.695	2.651	2.624
H1	Ad -161	11/2/2017	4221.1	500.0	4530.1	22.6	1000.0	617.6	0.661	2.632	2.604	2.587
H2	Ad -161	1/2/2018	4220.2	500.0	4529.6	22.7	1000.0	618.2	0.663	2.636	2.608	2.591
I1	BN-59s	10/31/2017	4220.5	500.0	4532.7	22.7	1000.0	622.2	0.327	2.664	2.650	2.641
I2	BN -59s	1/2/2018	4220.2	500.0	4532.0	22.6	1000.0	622.2	0.483	2.664	2.643	2.630
I3	Bn59s	4/12/2018	4221.1	500.0	4532.7	28.1	1000.0	620.6	0.343	2.657	2.642	2.633
J1	Cn - 140c	11/7/2017	4220.7	500.0	4530.6	22.9	1000.0	619.2	0.648	2.643	2.615	2.599
J2	Cn - 140c	1/4/2018	4220.3	500.0	4529.7	22.7	1000.0	618.7	0.723	2.639	2.609	2.590
K1	Bn - 156c	11/7/2017	4220.7	500.0	4532.0	23.0	1000.0	620.9	0.413	2.655	2.637	2.626
K2	Bn 156c	1/5/2018	4220.6	500.0	4531.8	22.8	1000.0	621.6	0.586	2.660	2.634	2.619
L1	Le - 160c	11/9/2017	4221.0	500.0	4531.7	22.8	1000.0	623.7	1.219	2.675	2.622	2.590
L2	Le 160c	1/18/2018	4220.9	500.0	4530.9	22.8	1000.0	624.6	1.673	2.681	2.609	2.566
L3	Le 160c	2/13/2017	4221.1	500.0	4531.4	28.1	1000.0	625.2	1.786	2.690	2.612	2.566
M1	Cl -56s	11/9/2017	4221.0	500.0	4531.4	22.8	1000.0	620.8	0.764	2.654	2.621	2.602
M2	Cl -56s	1/4/2018	4220.3	500.0	4531.4	22.7	1000.0	622.9	0.881	2.669	2.631	2.608
N1	Kt -222	11/30/2017	4220.1	500.0	4535.9	23.0	1000.0	630.2	0.511	2.722	2.699	2.685
N2	Kt -222	1/9/2018	4220.4	500.0	4536.4	22.6	1000.0	630.8	0.523	2.726	2.702	2.688
N3	Kt 222c	2/14/2018	4220.8	500.0	4536.4	27.8	1000.0	629.7	0.574	2.722	2.696	2.681
O1	Bg -111c	11/30/2017	4220.1	500.0	4530.9	23.0	1000.0	620.4	0.551	2.652	2.628	2.613
O2	Bg 111c	1/18/2018	4220.0	500.0	4531.3	27.8	1000.0	620.4	0.435	2.655	2.636	2.625
P1	Kt -215	11/28/2017	4220.6	500.0	4533.6	23.3	1000.0	629.5	1.486	2.717	2.651	2.612
P2	Kt 215	1/5/2018	4220.6	500.0	4533.9	23.2	1000.0	628.1	1.049	2.707	2.660	2.632
P3	Kt 215	2/16/2018	4220.7	500.0	4534.1	28.0	1000.0	629.6	1.428	2.722	2.657	2.620
Q1	ID -256	11/28/2017	4220.6	500.0	4541.3	22.8	1000.0	646.6	1.792	2.849	2.760	2.711
Q2	ID -256	1/5/2018	4220.6	500.0	4541.5	22.8	1000.0	647.4	1.851	2.856	2.763	2.712

Table A.1 continued (Note all weights are in grams)

UI - ID	ITD - ID	Date	Average Container Calibration Weight	Average Dry Sample Weight	Average Sample Weight in Container Filled with Water	Bag Weight	Dry Sample Weight	Weight of Sealed Sample Opened in Water	Percent Absorption	Apparent Density	Bulk Specific Gravity (SSD)	Bulk Specific Gravity (BSG)
R1	Bk - 100c	12/26/2017	4220.5	500.0	4533.7	22.8	1000.0	625.3	0.547	2.686	2.662	2.647
R2	Bk - 100c	1/9/2018	4220.4	500.0	4536.0	23.2	1000.0	626.5	0.437	2.695	2.676	2.664
R3	Bk100c	4/12/2018	4221.1	500.0	4534.2	28.3	1000.0	624.6	0.545	2.686	2.661	2.647
S1	Bg -107c	12/27/2017	4220.6	500.0	4531.4	22.6	1000.0	620.8	0.602	2.654	2.628	2.612
S2	Bg 107c	1/18/2018	4220.0	500.0	4531.4	28.0	1000.0	620.7	0.459	2.658	2.638	2.625
S3	Bg 107c	2/16/2018	4220.7	500.0	4531.5	28.1	1000.0	620.2	0.600	2.654	2.628	2.612
T1	WCW 18	12/26/2017	4220.5	500.0	4547.1	22.8	1000.0	658.6	1.812	2.950	2.851	2.801
T2	WCW 18c	1/9/2018	4220.4	500.0	4547.5	22.7	1000.0	660.2	1.948	2.964	2.857	2.802
U1	Bl -93s	12/27/2017	4220.6	500.0	4532.1	22.7	1000.0	622.2	0.584	2.664	2.639	2.623
U2	Bl -93s	1/18/2018	4220.9	500.0	4532.2	28.3	1000.0	621.2	0.584	2.661	2.636	2.621
U3	Bl 93s	2/16/2018	4220.7	500.0	4532.3	28.2	1000.0	621.5	0.543	2.663	2.640	2.625
V1	Np 82c	1/2/2018	4220.2	500.0	4547.2	22.9	1000.0	654.4	0.865	2.914	2.867	2.843
V2	Np 82c	1/18/2018	4220.0	500.0	4547.3	28.0	1000.0	654.4	0.835	2.919	2.873	2.849

Table A.2 Raw data for the AASHTO T-84 Tests (Note all weights are in grams)

UI - ID	ITD - ID	Date	Wt. of Pycnometer	Pycn+ Water	Pycn+ SSD Sample	SSD Sample	Pycn +Water +Sample	Wt of Pan	Dry weight with pan	Dry wt	Remarks
A1	Ad 136	2/21/2017	186.0	685.0	707.5	521.5	1006.5	238.5	754.0	515.5	
A2	Ad 136	2/21/2017	190.5	689.5	720.0	529.5	1015.0	246.5	769.5	523.0	
A3	Ad 136	2/21/2017	182.0	681.0	706.5	524.5	1005.0	243.0	761.5	518.5	
A4	Ad 136	2/21/2017	201.0	700.0	742.5	541.5	1034.0	243.5	779.0	535.5	
A5	Ad 136	8/25/2017	185.9	684.3	722.1	536.2	1016.1	784.5	1315.4	530.9	
B1	Fr 104c	2/28/2017	190.6	689.6	698.4	507.8	991.1	251.5	742.6	491.1	
B2	Fr 104c	2/28/2017	186.1	685.1	705.4	519.3	994.3	90.1	592.4	502.3	
B3	Fr 104c	3/1/2017	186.1	685.1	713.0	526.9	998.9	243.4	753.4	510.0	
B4	Fr 104c	3/1/2017	190.6	689.6	706.1	515.5	996.2	243.3	741.9	498.6	
B5	Fr 104c	9/8/2017	190.4	688.6	690.4	500.0	986.9	780.9	1265.4	484.5	
C1	WCW 23	2/22/2017	190.5	689.5	718.0	527.5	1029.5	251.5	763.9	512.4	
C2	WCW 23	2/22/2017	182.0	681.0	731.0	549.0	1033.5	86.1	619.0	532.9	
C3	WCW 23	2/22/2017	186.0	685.0	718.0	532.0	1027.5	120.0	637.2	517.2	
C4	WCW 23	2/22/2017	190.5	689.5	723.0	532.5	1033.0	90.0	608.4	518.4	
C5	WCW 23	4/12/2017	190.5	689.5	694.2	503.7	1014.5	251.5	742.0	490.5	
C6	WCW 23	4/12/2017	186.0	685.0	716.5	530.5	1027.0	243.3	759.5	516.2	
C7	WCW 23	9/12/2017	190.4	688.6	690.4	500.0	1012.4	780.9	1268.5	487.6	
C8	WCW 23	9/14/2017	190.4	688.6	695.5	505.1	1015.4	780.8	1273.3	492.5	
D1	Kt 213	2/23/2017	190.5	689.5	691.4	500.9	1002.1	243.4	737.2	493.8	
D2	Kt 213	2/23/2017	186.0	685.0	716.7	530.7	1015.0	243.0	766.1	523.1	
D3	Kt 213	2/24/2017	186.0	685.0	705.3	519.3	1007.4	238.8	749.8	511.0	
D4	Kt 213	2/24/2017	190.5	689.5	700.5	510.0	1006.3	246.8	750.3	503.5	
D5	Kt 213	8/30/2017	190.4	688.6	694.5	504.1	1004.8	784.5	1283.4	498.9	
D6	Kt 213	2/14/2018	181.7	680.4	726.2	544.5	1020.6	251.6	788.7	537.1	

Table A.2 continued (Note all weights are in grams)

UI - ID	ITD - ID	Date	Wt. of Pycnometer	Pycn+ Water	Pycn+ SSD Sample	SSD Sample	Pycn +Water +Sample	Wt of Pan	Dry weight with pan	Dry wt	Remarks
E1	Ad 182	7/21/2017	190.4	688.6	707.5	517.1	1004.1	780.9	1292.2	511.3	
E2	Ad 182	8/21/2017	190.4	688.6	719.8	529.4	1014.0	784.5	1308.9	524.4	
E3	Ad 182	8/24/2017	190.4	688.6	732.3	541.9	1021.9	780.8	1317.2	536.4	
F1	Le -96s	11/2/2017	274.7	1271.6	776.6	501.9	1585.3	780.5	1279.2	498.7	1000 ml flask
F2	Le -96s	1/2/2018	190.4	688.6	715.6	525.2	1016.2	244.9	766.5	521.6	
F3	Le 96 s	2/13/2018	208.2	706.8	736.9	528.7	1036.6	243.3	768.6	525.3	
G1	Cu -75s	10/31/2017	190.4	689.5	714.0	523.6	1014.1	244.7	760.2	515.5	500ml flask
G2	Cu -75s	10/31/2017	274.7	1271.6	841.1	566.4	1624.0	239.5	797.3	557.8	1000 ml flask
G3	Cu -75s	1/4/2018	182.0	681.0	723.5	541.5	1016.6	780.9	1313.7	532.8	
H1	Ad -161	11/2/2017	190.4	689.5	693.7	503.3	998.6	120.2	618.1	497.9	
H2	Ad -161	1/2/2018	201.0	700.0	746.7	545.7	1042.1	243.2	782.5	539.3	
H3	Ad -161	4/11/2018	181.7	680.4	707.0	525.3	1003.2	238.7	758.3	519.6	
I1	BN -59s	10/31/2017	186.0	685.0	700.5	514.5	1004.5	251.5	763.6	512.1	
I2	BN -59s	1/2/2018	182.0	681.0	692.3	510.3	997.8	780.8	1288.5	507.7	
J1	Cn - 140c	11/7/2017	190.4	689.5	693.1	502.7	998.5	89.3	586.9	497.6	
J2	Cn - 140c	1/4/2018	208.2	706.8	716.7	508.5	1019.6	243.2	745.8	502.6	
K1	Bn - 156c	11/7/2017	186.0	685.0	700.3	514.3	1003.5	784.3	1295.1	510.8	
K2	Bn 156c	1/5/2018	190.4	688.6	726.9	536.5	1021.4	91.5	623.6	532.1	
L1	Le - 160c	11/9/2017	190.4	689.5	711.4	504.7	1002.9	91.5	588.8	497.3	
L2	Le 160c	1/15/2018	201.0	700.0	711.1	510.1	996.9	89.3	591.4	502.1	
L3	Le 160c	2/13/2018	181.7	680.4	683.6	501.9	992.2	239.6	733.8	494.2	
M1	Cl -56s	11/9/2017	186.0	685.0	690.7	521.0	1007.5	244.7	761.3	516.6	
M2	Cl -56s	1/4/2018	190.4	688.6	715.1	524.7	1013.7	244.8	764.5	519.7	

Table A.2 continued (Note all weights are in grams)

UI - ID	ITD - ID	Date	Wt. of Pycnometer	Pycn+ Water	Pycn+ SSD Sample	SSD Sample	Pycn +Water +Sample	Wt of Pan	Dry weight with pan	Dry wt	Remarks
N1	Kt -222	11/30/2017	190.4	689.5	713.3	522.9	1017.2	758.4	1276.3	517.9	
N2	Kt 222	1/9/2018	208.2	706.8	718.9	510.7	1027.2	243.3	748.7	505.4	
N3	Kt 222	2/14/2018	208.2	706.8	756.9	548.7	1050.9	243.2	786.0	542.8	
O1	Bg -111c	11/30/2017	186.0	685.0	738.3	552.3	1026.5	780.5	1329.4	548.9	
O2	Bg 111c	1/11/2018	190.4	688.6	691.6	501.2	999.5	91.4	589.3	497.9	
P1	Kt -215	11/28/2017	186.0	685.0	694.1	508.1	1002.4	780.5	1282.8	502.3	
P2	Kt 215	1/5/2018	208.2	706.8	724.0	515.8	1029.4	120.3	630.0	509.7	
Q1	ID -256	11/28/2017	190.4	689.5	714.0	523.6	1020.9	758.4	1269.1	510.7	
Q2	ID -256	1/5/2018	181.7	680.4	709.4	527.7	1014.9	89.4	603.5	514.1	
R1	Bk - 100c	12/26/2017	186.0	685.0	688.8	502.8	998.3	73.0	571.3	498.3	
R2	Bk - 100c	1/9/2018	181.7	680.4	687.5	505.8	995.6	243.2	744.6	501.4	
S1	Bg -107c	12/27/2017	201.0	700.0	713.0	512.0	1023.6	780.9	1289.2	508.3	
S2	Bg 107c	1/11/2018	182.0	681.0	696.1	514.1	999.2	89.3	600.0	510.7	
S3	Bg 107c	2/16/2018	208.2	706.8	720.3	512.1	1024.0	243.2	752.0	508.8	
T1	WCW 18	12/26/2017	190.4	688.6	769.5	579.1	1064.2	73.1	636.4	563.3	
T2	WCW 18	1/9/2018	190.4	688.6	746.9	556.5	1049.6	244.8	787.1	542.3	
U1	Bl -93s	12/27/2017	190.4	688.6	709.6	519.2	1011.1	784.7	1300.7	516.0	
U2	Bl -93s	1/17/2018	208.2	706.8	725.8	517.6	1027.5	243.1	757.2	514.1	
U3	Bl -93s	2/16/2018	181.7	680.4	695.7	514.0	999.5	239.6	750.3	510.7	
V1	Np 82c	1/1/2018	190.4	688.6	722.6	532.2	1033.3	243.3	762.8	519.5	
V2	Np 82c	1/17/2018	181.7	680.4	696.3	514.6	1013.6	243.3	745.6	502.3	